TESTING OF A 20-METER SOLAR SAIL SYSTEM

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ABSTRACT

This paper describes the structural dynamic tests conducted in-vacuum on the Scalable Square Solar Sail (S^4) System 20-meter test article developed by ATK Space Systems as part of a ground demonstrator system development program funded by NASA's In-Space Propulsion program. These tests were conducted for the purpose of validating analytical models that would be required by a flight test program to predict in space performance. Specific tests included modal vibration tests on the solar sail system in a 1 Torr vacuum environment using various excitation locations and techniques including magnetic excitation at the sail quadrant corners, piezoelectric stack actuation at the mast roots, spreader bar excitation at the mast tips, and bi-morph piezoelectric patch actuation on the sail cords. The excitation methods are evaluated for their suitability to in-vacuum ground testing and their traceability to the development of on-orbit flight test techniques. The solar sail masts were also tested in ambient atmospheric conditions and these results are also discussed.

INTRODUCTION

NASA Langley Research Center and ATK Space Systems performed structural dynamic tests on the S^4 20-meter solar sail system in the 30-meter vacuum chamber (Space Power Facility) at the NASA Glenn Plum Brook facility in Sandusky, Ohio. A series of twelve tests, shown in Table 1, were aimed at determining the dynamics of the sail system once deployed and tensioned. Sail dynamics are influenced by the membrane geometry, mass distribution, three-point sail tensioning forces, distributed membrane stresses, sail seam characteristics, folding creases, gravity in the 1g environment (or solar pressure on orbit), etc. Therefore developing test plans and methods that take into account all these variables is extremely important. Since the masts are the primary load bearing members, it is also important to measure their dynamics separately.

The sail dynamics measurements were made using vibrometry at 1 Torr vacuum conditions inside the Plum Brook vacuum chamber. For the baseline test configuration, the sail spreader bars were horizontal, and then they were rotated 22.5 degrees from horizontal for another sequence of tests. The vibrometer scanner head is located inside an environmentally controlled canister that can operate in the vacuum conditions. Single Point Laser Vibrometry

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requires acquiring response measurements at retro-reflective target locations sequentially (one target at a time) and then post processing the results to determine system dynamic response behavior. Thus, it was important that the sail remain in a consistent configuration during the scanning period (which can be many hours for many target locations) to avoid data inconsistencies.

SAIL SYSTEM TEST CONFIGURATION

The test article is oriented parallel to the ground within the chamber, and off loaded during testing by an ATK-supplied, floor-mounted trolley system that supports each mast tip. Figure 1 shows the 20-meter S^4 system in its deployed test configuration inside the Plum Brook vacuum chamber. The numbering of the sail quadrants and sail corners relative to the mast names and the coordinate reference frame is indicated. For dynamics tests, the sail mast tips are off loaded with a negator spring system designed by ATK that provides a low frequency suspension to minimize interference with sail system dynamics. Measurements for the dynamics tests are made at retro-reflective targets strategically positioned throughout the sail system, as can be seen in Figure 1. These targets allow for the laser signal to be properly returned to the scan head for accurate velocity measurements off the target surface.

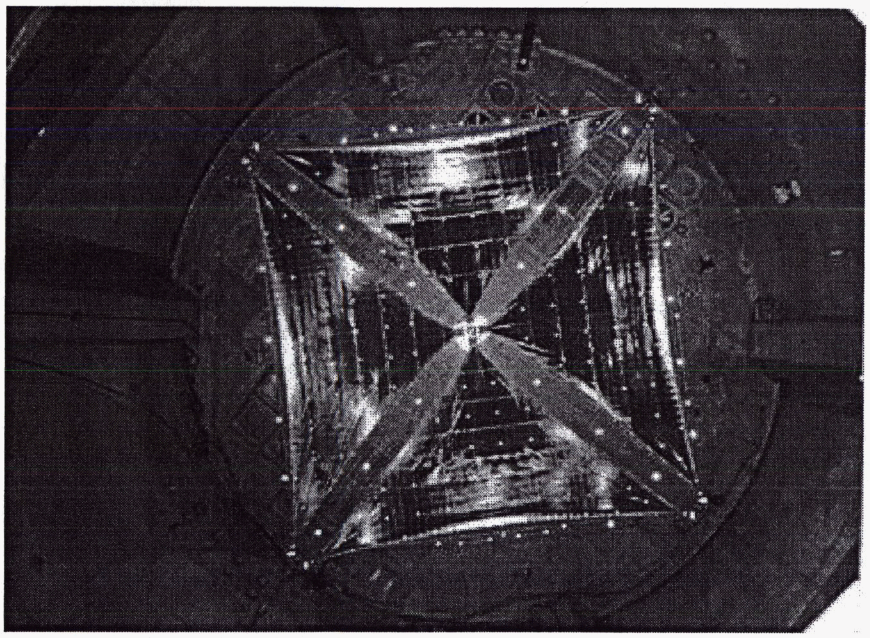

Figure 1. 20-meter Solar Sail inside Vacuum Chamber

Dynamic testing is carried out with the solar sail assembly in the fully deployed orientation. The sail membranes are supported between the masts by a constant force suspension arrangement at the mast tip attachment of each sail quadrant. This arrangement yields predictable stresses within the sail membrane and masts and compensates for any thermally induced dimensional changes. The dynamics of the membrane/system will be evaluated at a single nominal sail tension of ~2.5 lbs. of halyard load, and at a baseline of zero degree spreader bar angle and then at an angle of 22.5 degrees from horizontal. Both of the moveable Attitude Control System (ACS) ballast masses are stowed inside the central assembly during dynamic testing.

The vibrometer test configuration consists of the vibrometer canister mounted on the chamber door ledge and oriented so the laser beam points up toward the center of the dome and crane structure above. Due to insurmountable limitations on the maximum length allowed for the vibrometer scan head cable (30-meters), the vibrometer cable is not long enough to allow for positioning the instrument directly overhead of the test article. Therefore, an active Scanning Mirror System (SMS) that can receive the laser beam from the vibrometer and redirect it toward the test article below for dynamic response measurement is mounted directly above the test article on a crane structure, about 20-meters from the vibrometer. This configuration is illustrated in Figures 2 and 3. The SMS system is composed of two mirrors mounted on galvanometer motors that are oriented orthogonal to one another to allow for two axis scanning with a range of +/- 20 degrees. The galvanometer motors have similar pointing accuracy specifications to those used in the vibrometer scanner system (Polytec PSV-400), which allows for precision target tracking from large distances. A specially developed target tracking algorithm enables automatic centering of the laser beam on each retro-reflective target to be measured. Prior to this test, the vibrometer scanning system was validated to work at 85-meters range (although larger distances are possible), well beyond the required working distance of 60-meters for our configuration.

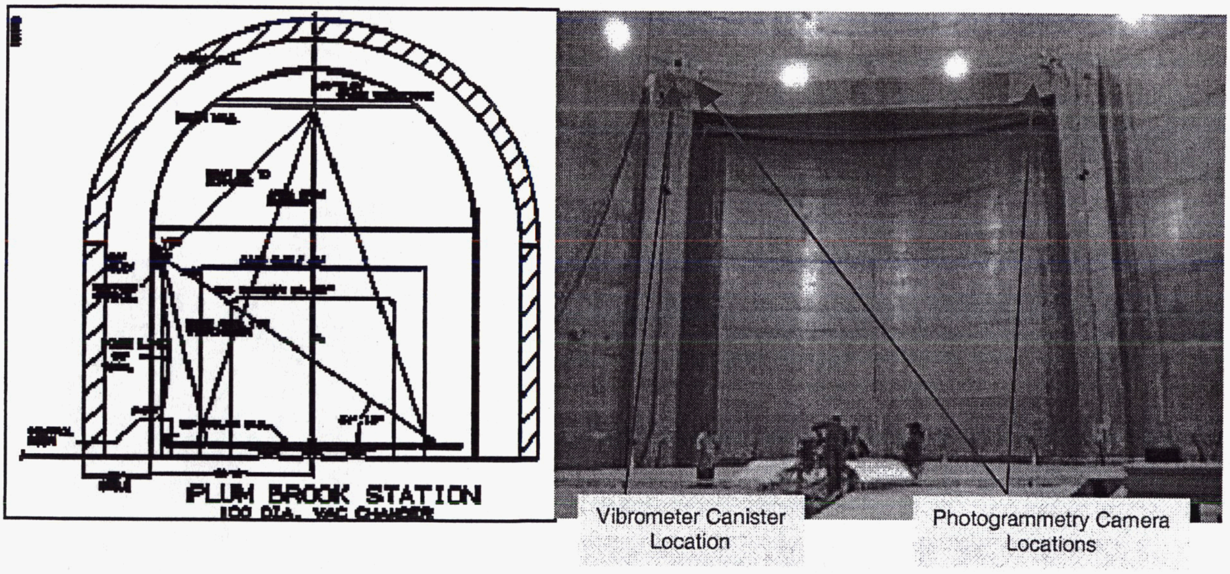

Figure 2. Instrumentation inside Vacuum Chamber

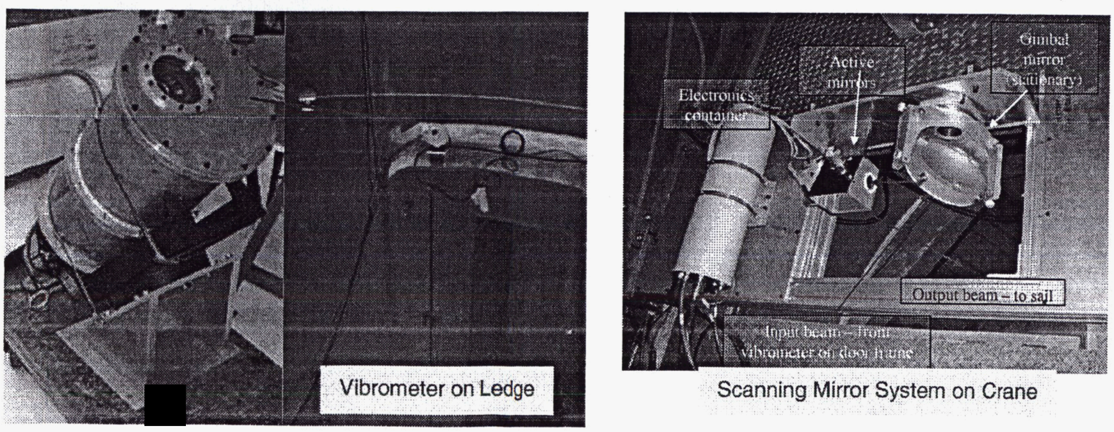

Figure 3. Vibrometer and Scanning Mirror System inside Vacuum Chamber

The baseline excitation method for the tests consists of using electro-magnets mounted at each sail membrane quadrant corner. A total of 12 magnets are precisely aligned at the corners of each sail (3 magnets per sail quadrant). In addition, magnets are positioned on the long cord at the center of the hypotenuse of each sail quadrant, as shown in Figure 4, to allow for capturing modes not possible to excite from the halyard corners. The halyard corner magnets (located near the mast tips) and the hypotenuse magnets are mounted on vertical translation stages with linear actuators for precise remote positioning of the magnets in-vacuum. The magnets need to be positioned within 5-mm of the sail to work properly, so small CMOS cameras are positioned next to each magnet and carefully aligned to validate that the proper gap size is achieved.

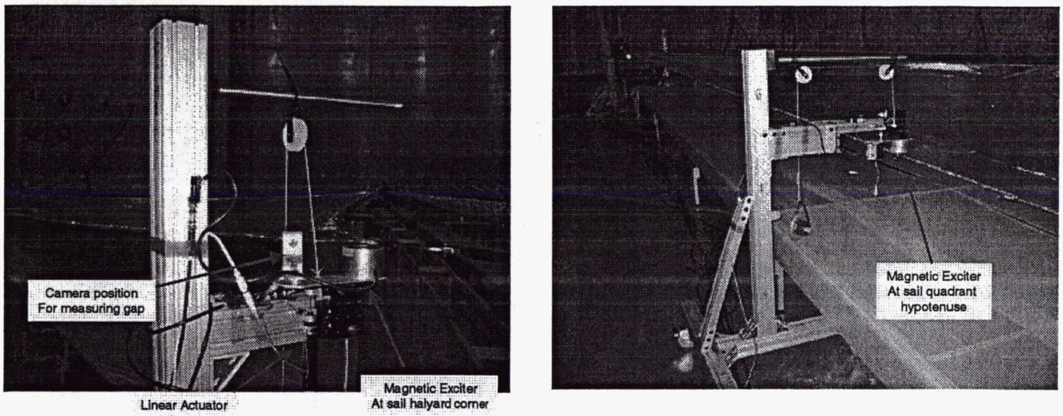

Figure 4. Magnetic Exciter System Configuration

To reduce sail motion during vacuum pump down the mast tips are secured with an electro-magnet, shown in Figure 5, that prevents vertical and lateral motion. During pump down, a constant voltage is supplied to the mast tip electro-magnets to prevent motion due to air currents. Once at vacuum the voltage to the electro-magnet is removed, allowing the spring to pull the magnet away from the test article. The mast tips are then free to move with the soft suspension system off-loader, shown in Figure 5.

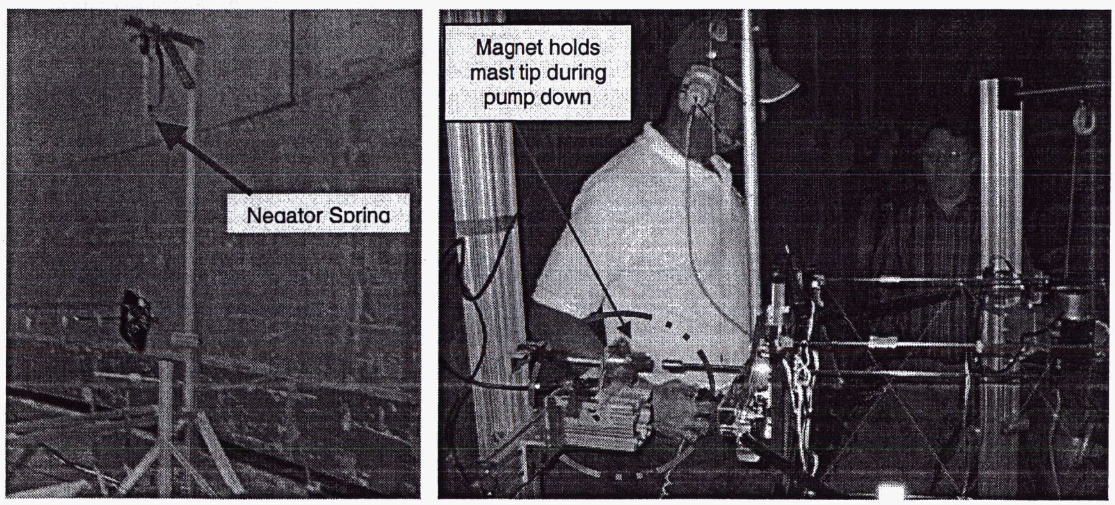

Figure 5. Mast Tip Off-loaded with Negator Spring and Fixed During Pump Down

SAIL SYSTEM TEST RESULTS AND DISCUSSION

Table 1 summarizes the twelve in-vacuum dynamics tests completed on the sail in the zero degree spreader bar configuration. Most of the team's effort for this series of tests was focused on getting the best quality data possible on quadrant 4, as this quadrant was the most pristine sail membrane with few flaws and it had flight-like characteristics, such as rip stops, built into the membrane. Quadrant 3 was tested second with a reduced set of measurements since it was the next best quality quadrant with some differences from quadrant 4, such as the lack of rip-stops. Quadrants 2 and 1 were tested last with a reduced set of measurements, since these quadrants were of least interest for model correlation. Quadrant 2 had a major repair, while quadrant 1 had been used to develop and validate deployment methods and as a result had many wrinkles and small repairs. The quadrant tests were followed by a full sail system test in-vacuum, in which one halyard corner magnet on each quadrant is driven simultaneously and in-phase with a sine sweep excitation. This technique allows for adequate excitation of the entire sail system and allows for the identification of major system level vibration modes. To save test time, the full sail system test only measured 5 sail membrane locations per quadrant and two mast tip measurements per mast. Since the test article configuration did not change going from the quadrant tests to full sail system testing, the high spatial resolution quadrant test results could be compared with the lower spatial resolution system test results to make an assessment as to how the quadrants respond at each system level mode.

Table 1. Sail Dynamics Tests Completed In-Vacuum

System Tests with 0 Degree Spreader Bar (Sail Halyard Magnetic Excitation) – Vacuum			
#	Test Name	Meas. #	Explanation
1	Q4M1M2 - Mast Tips Fixed	11	Check-out techniques while mast tips are fixed with magnetic restraint
2	Q4M1 - Mast Tips Fixed	7	Check-out techniques while mast tips are fixed with magnetic restraint
3	Q4M1 - Test DC offset method – Tips Free	13	Check-out techniques with mast tips free to float on soft suspension system
3	Q4M1M2 – Test DC offset method – Tips Free	13	Check-out techniques with mast tips free to float on soft suspension system
4	Q4M1M2 – Sail Quad	44	1st baseline test on Quad 4 with M1 & M2 excitation out-of-phase
5	Q4M1 – Sail Quad	44	2nd baseline test on Quad 4 with M1 excitation
6	Q4M2 – Sail Quad	44	3rd baseline test on Quad 4 with M2 excitation
7	Q3M1M2 – Sail Quad	15	1st baseline test on Quad 3 with M1 & M2 excitation out-of-phase
8	Q3M1 – Sail Quad	15	2nd baseline test on Quad 3 with M1 excitation
9	Q1M1M2 – Sail Quad	15	Only baseline test on Quad 1 with M1 & M2 excitation out-of-phase
10	Q2M1M2 – Sail Quad	13	Only baseline test on Quad 2 with M1 & M2 excitation out-of-phase
12	Full Sail System – All Quads with M1	28	Only baseline test on Full Sail System with M1 excitation on each Quad in-phase

During the chamber pump down process, the sail sagged significantly (over 3 inches); it was discovered this sag was caused by moisture build up on the sail during chamber pump down, which added weight to the sail. The Plum Brook chamber produces a large moisture build-up (Fog) during pump down. The additional weight from the moisture on the sail caused the halyard negators to pay out the cord at the mast tips and the resulting sag at the center of the sail hypotenuse was sufficiently large that the linear actuators could not reposition the magnets close enough (within 5 mm) to the sail for proper excitation. Since the magnets were mounted above the sails for this test, the only impact was that the magnets on the hypotenuse were useless for excitation, which limited testing to using only halyard corner magnets for sail excitation. Ultimately, this did limit the mode shapes that were excited, as will be discussed later. All the tests used either one or both remaining halyard magnets for sail excitation.

Analysis of the test data began by reviewing the Frequency Response Functions (FRFs) from each quadrant test, and identifying and listing all the resonant frequencies. Each of these modes where then categorized as to how well it was excited and identified in the FRFs. Modes with well-defined peaks in most FRFs were given a data quality rank of 1, or 1- for somewhat lower quality peaks. Modes with well-defined peaks, but perhaps closely coupled to other modes and/or in the residual of other modes as identified in the FRFs, were given a rank of 2 or perhaps 2- for modes of lower quality. Modes of potential interest that were in frequency ranges of high modal density and/or significantly buried in residuals of other modes were ranked a 3. Only modes with a rank of 2+ or better that also repeated well for every quadrant test (with only minor frequency differences) were considered to be successfully obtained and marked as useful for analytical model correlation. Only the data from the quadrant 4 tests were utilized for model correlation. The other quadrant tests were performed primarily to determine the differences between quadrants and their influence on system response behavior. Table 2 summarizes the dominant modes identified through this review process for the quadrant 4 tests.

Table 2. Sail Quadrant 4 Dynamics In-Vacuum Test Results

ID #	SUMMARY of DOMINANT MODES			
	Hz	Rating	Description	Notes
1	0.391	1	Sail Vertical Motion / Heavily Damped Non-linear Mechanism Mode	Potentially related to negator springs in halyard and/or on mast tip
2	0.503	1	**Sail System 1st Mode "Pin Wheel Mode"** Sail Rocking / All Mast Tips Twist in-phase	Mast Dominant Mode, sail follows
3	0.625	1-	Sail Rocking / Y Tips OOP / Z Tips OOP	Mast Dominant Mode, sail follows
4	0.687	2+	**Sail Membrane 1st Breathing Mode** Long Cord 1st Bending / Centerline 1st Bending	Membrane Mode, 1st centerline
5	0.937	2+	Long Cord 1st Bending / Centerline 2nd Bending (1)	Membrane Mode, 2nd centerline
6	1.0	2+	Long Cord 1st Bending / Centerline 2nd Bending (2)	Membrane Mode, 2nd centerline
7	1.06	1	Asymmetric Sail Mode LT Side Short Cord & RT Side Long Cord OOP	Mast Dominant Mode, sail flex, Full system response
8	1.41	1-	Long Cord 1st Bending / Centerline 3rd Bending (1)	Membrane Mode, 3rd centerline
9	1.47	2+	Long Cord 1st Bending / Centerline 3rd Bending (2)	Membrane Mode, 3rd centerline

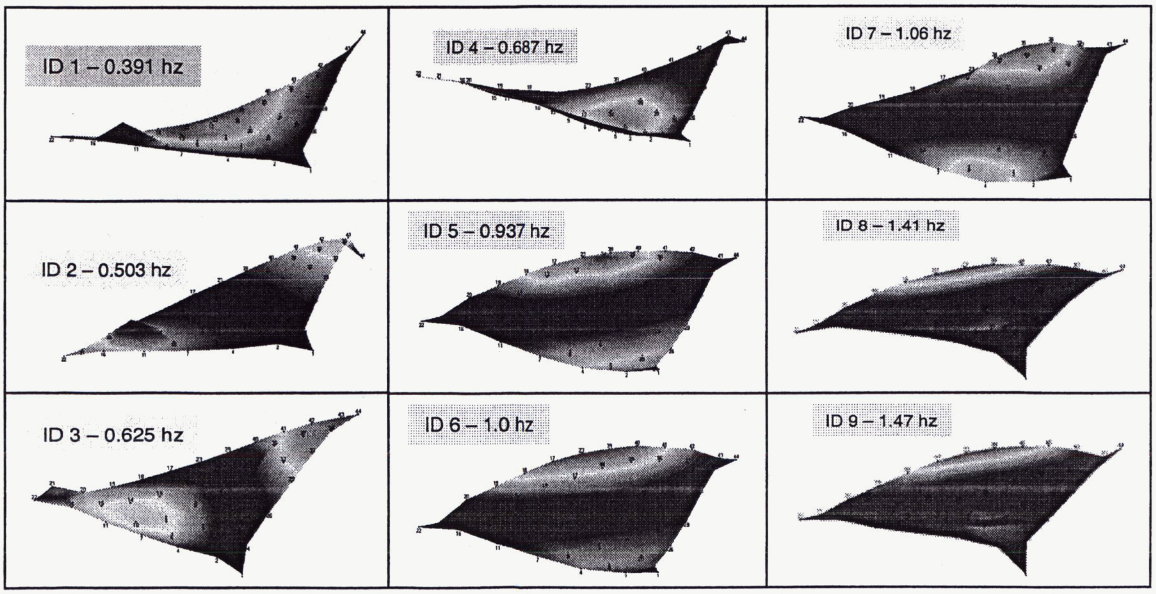

Figure 6. Summary of Dominant Operating Deflection Shape (ODS) Modes

Mode 1, as identified in Table 2 and Figure 6, is a dominant heavily damped mode with a damping factor of ~20%. This is significantly higher than all the other modes that have damping factors in the 2-3 percent range, which is more typical of a structural mode of vibration. The high damping indicates mode 1 is a non-structural mechanism mode, which may be caused by a non-linearity due to free-play or sliding friction. It is believed this non-linearity may have been introduced through the mechanism holding the system at the mast tips or through the sail membrane cord negator springs. The mast tip is supported by negator springs that are left unlocked during testing to allow for mast tip vertical motion, to minimize dynamic interference with the sail system. The sail membrane is also supported by negator springs at the mast tip halyards designed to allow for constant loading during thermal expansion, however this could also allow for cord sliding friction during dynamic excitation.

By comparing quadrant test results with system test results, it was found modes 2, 3 and 7 are primarily mast-dominated modes with the sail motion following the mast tips. Mode 2 is the first full system mode, where each sail membrane is rocking and pivoting about the quadrant centerline.

Modes 4-6 and 8-9 are sail membrane dominated modes. Mode 4 is a sail membrane 1st breathing mode, with the long cord in 1st bending and the quadrant centerline also in 1st bending. The other sail dominant modes are all in 1st bending along the long cord, but undergo various degrees of bending down the quadrant centerline starting with 2nd bending for modes 5-6 and then to 3rd bending for modes 8-9.

Modes 1-4 and 7-9 were easily identified in all the quadrant test data. Modes 5 and 6 were strong for most tests, but were not consistently excited for some. Figure 7 shows how modes 5 and 6 were well excited on quadrant 4 when using 1 halyard magnet exciter, but not for the other. It turns out that this mode is difficult to excite from the halyard corners, since these locations are near a node-line for the mode shape. The goal was to use the exciters at the quadrant hypotenuse for modes like these, but as mentioned previously the sail sag shifted the sail quadrant hypotenuse out of range for the exciter. This limited the testing to using only halyard magnets. Another limitation found was that no 2nd and 3rd order modes on the hypotenuse could be excited with the halyard magnets being at the node-line for these modes.

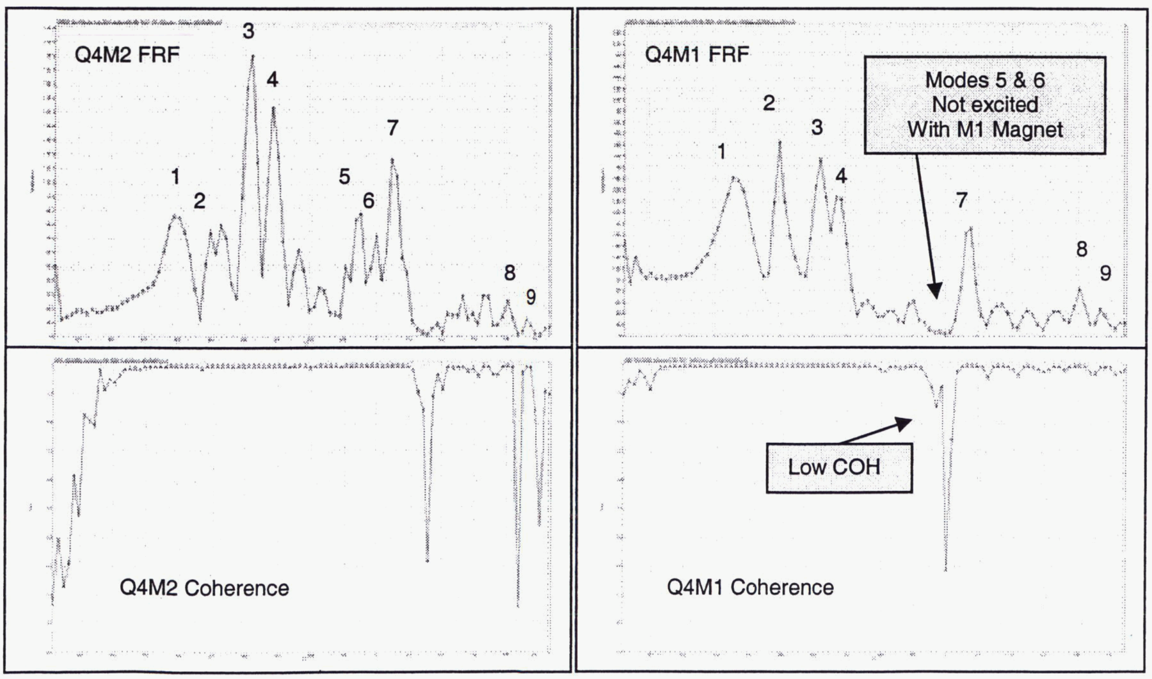

Figure 7. Response Measurement Comparison – M1 versus M2 Magnetic Exciter

The full sail system test shows exceptionally strong mast participation for modes 2 and 7, as shown in Figure 8. These are system level mast dominated modes with the sail membrane following the mast as shown in the mode shapes. Mode 2, the 1st fundamental system mode of the solar sail, is a "Pin Wheel Mode" with all quadrants rocking in-phase. This mode is created by all mast tips twisting in-phase and the quadrants following the motion by rocking and pivoting about the quadrant centerline. Mode 7 is a mast-dominated mode with the sail membrane bending asymmetrically. In this asymmetric bending, the mast tips twist out-of-phase with one another at each quadrant halyard corner. Mode 3 at 0.625 Hz is another mast-dominated system mode. In this mode, the masts on quadrants 2 and 4 twist in-phase, causing the quadrants to rock by pivoting about their quadrant centerline. While the masts on quadrants 1 and 3 twist out-of-phase, causing these sail quadrants to rock about the centerline and also pitch forward-and-aft. The motion of mode 3 is best illustrated in Figure 9, where the darkest contour line (the mode shape node-line) represents the location about which the mode shape pivots. The labels in Figure 9 indicate which sail corners and mast tips are moving "up" or "down".

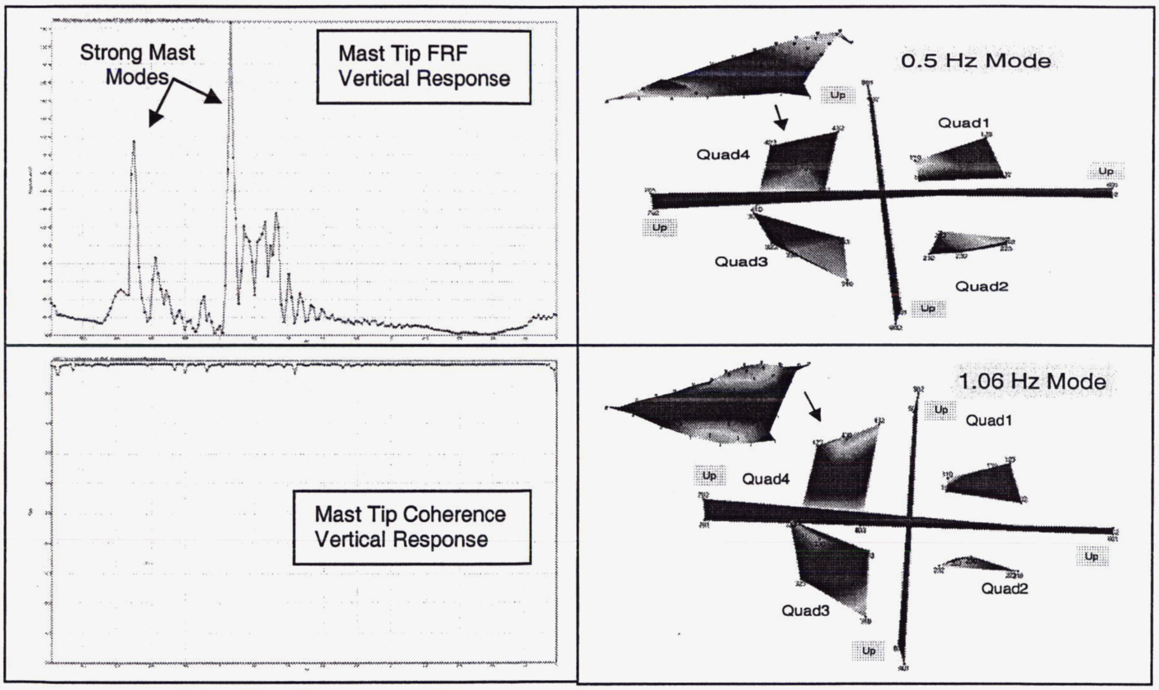

Figure 8. System Test Results showing the Mast Dominated Modes 2 and 7

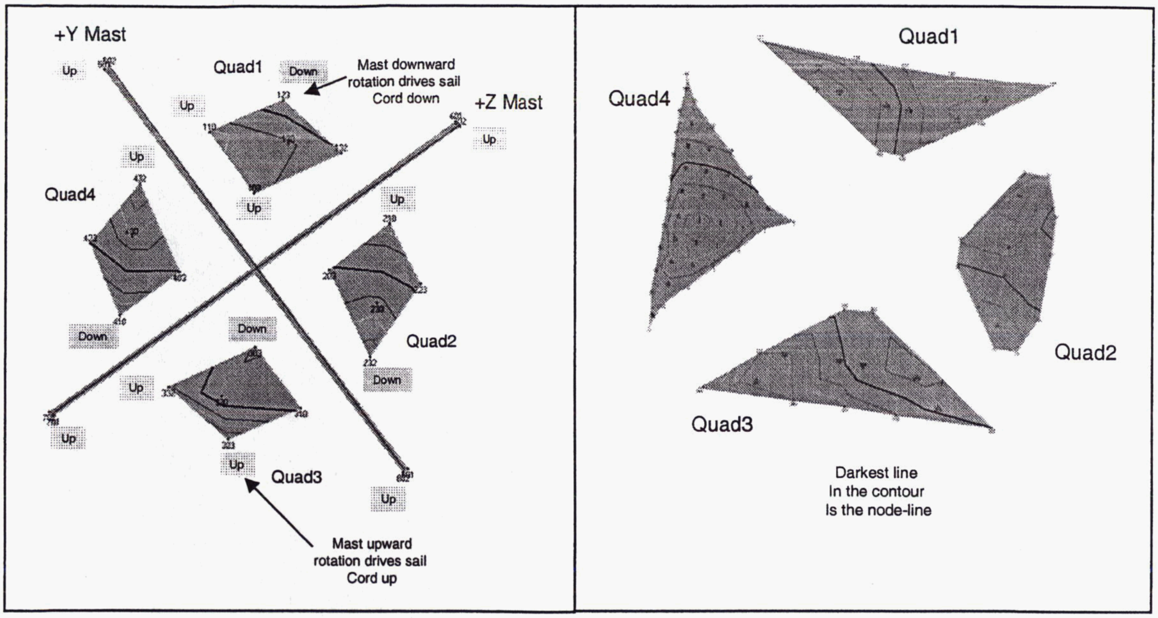

Figure 9. System and Quadrant Test Results showing the Mast Dominated Mode 3

MAST DYNAMICS TEST

The mast dynamics testing occurred immediately after the in-vacuum sail test. The chamber was vented so all the mast tests could be performed in ambient conditions. The sails were detached so mast only dynamics could be obtained. The baseline mast dynamics tests used piezo stack actuator excitation at the mast root. ATK Space Systems had pre-integrated piezo stack actuators at the root of each mast longeron, as shown in Figure 10, for the purpose of obtaining mast dynamics. This excitation configuration is a strong candidate for on-orbit flight-testing, and is considered the baseline test to which the Finite Element Model (FEM) analysis results are to be correlated. It was found that one actuator located on the upper longeron could provide enough excitation force to excite the mast fundamental modes in the longitudinal, lateral, and torsion directions. Therefore, all the masts were tested by driving just one upper longeron and the response was measured at the mast tip in the longitudinal direction at the two upper longerons and in the lateral direction at the lower longeron. These measurements were made with the laser vibrometer and required a mirror to redirect the beam to measure the lateral motion on the lower longeron, as seen in Figure 10. By comparing the phase of these three responses at the mast tip, it was possible to determine if the mode was a dominant longitudinal bending mode, lateral bending mode, or torsion mode. Figure 11 shows the longitudinal and lateral response for the +Y axis mast tip. The FRFs and coherences were excellent from all the mast tests, with very well defined modal peaks and good coherence across the entire frequency spectrum. The consistency of the mast responses was excellent (see Table 3), with all 4 masts showing almost identical responses for all the fundamental modes. Thus, the piezo stack excitation at the mast root was very successful. This technique not only saved valuable testing time as no setup was required, but also has traceability toward flight-testing.

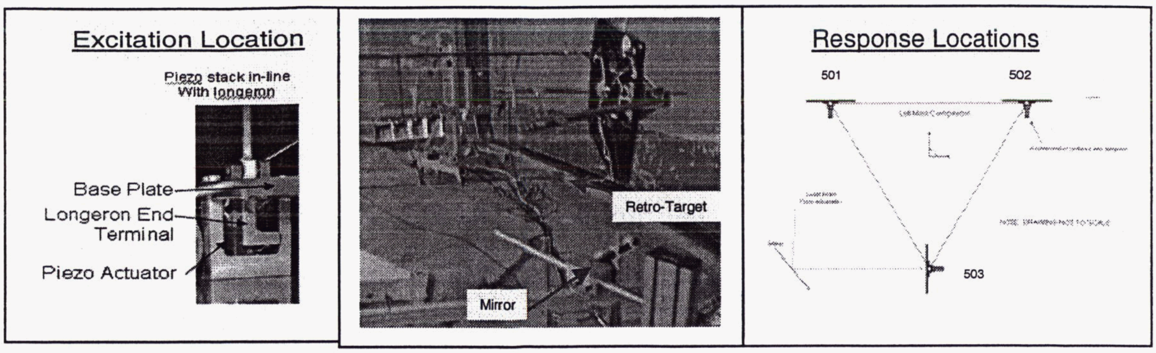

Figure 10. Mast Test Configuration in Ambient

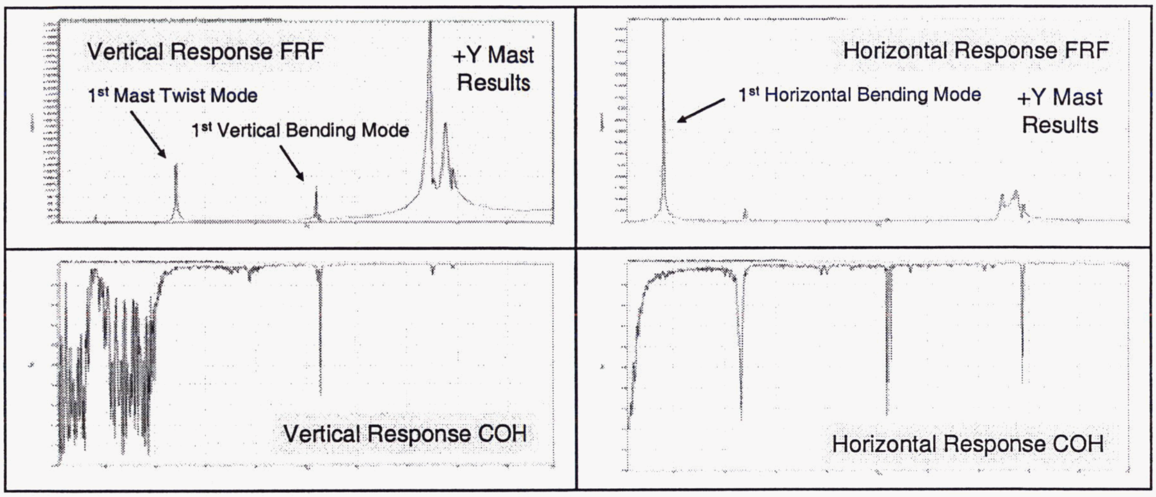

Figure 11. Mast Test Vertical and Horizontal Response Measurements

Table 3. Mast Dynamics Test Summary

#	Mode Description	Frequency Comparison (Hz)			
		+Y Mast	-Z Mast	-Y Mast	+Z Mast
1	Mast Bending in Horizontal Plane	0.813	0.813	0.797	0.797
2	Mast Twist	2.41	2.39	2.41	2.39
3	Mast Bending in Vertical Plane (-Z Mast)	NA	5.14	NA	NA
4	Mast Bending in Vertical Plane	5.22	5.23	5.27	5.30
5	Mast Bending in Vertical Plane (some twist on –z mast)	7.47	7.50	7.55	7.50
6	Mast 2nd Bending (only mast tips measured)	7.75	7.84	7.75	7.84

SAIL IN-VACUUM EXCITATION METHOD VALIDATION TESTS

In addition to the baseline tests which used a magnetic exciter technique for obtaining modal dynamics results for model correlation, there was also interest in evaluating other excitation methods that could potentially be used in future on-orbit test programs. In particular, three techniques were evaluated on the 20-m system at Plum Brook that included the piezo stack actuators at the mast root, spreader bar excitation at the mast tip, and bi-morph excitation on the sail cords with Macro Fiber Composite (MFC) piezoelectric patch actuators.

The first tests evaluated how well the piezo stack actuators at the mast root could excite system modes on quadrant 3. The two masts supporting quadrant 3 were excited in-phase and the system response was measured at 5 sail locations and two mast tip locations on each mast. Then the test was repeated by driving the masts out-of-phase. The method for driving the masts in-phase was to drive the MFCs on the upper longerons of each mast with the same input sine signal. The method for driving the masts out-of-phase was to drive one mast actuator at the lower longeron, while driving the other mast at the two upper longeron locations with the same input signals. It was found that piezo stack excitation at the mast root could excite the fundamental system level modes that are "mast dominated" very well, while the local sail membrane modes were not well excited. There was good response on both the sail and masts for these "mast dominated" modes, and as seen in Figure 12 the FRFs and coherences were excellent across the entire frequency spectrum. The identified modes, shown in Figure 13, matched those identified with the baseline magnetic excitation techniques very well.

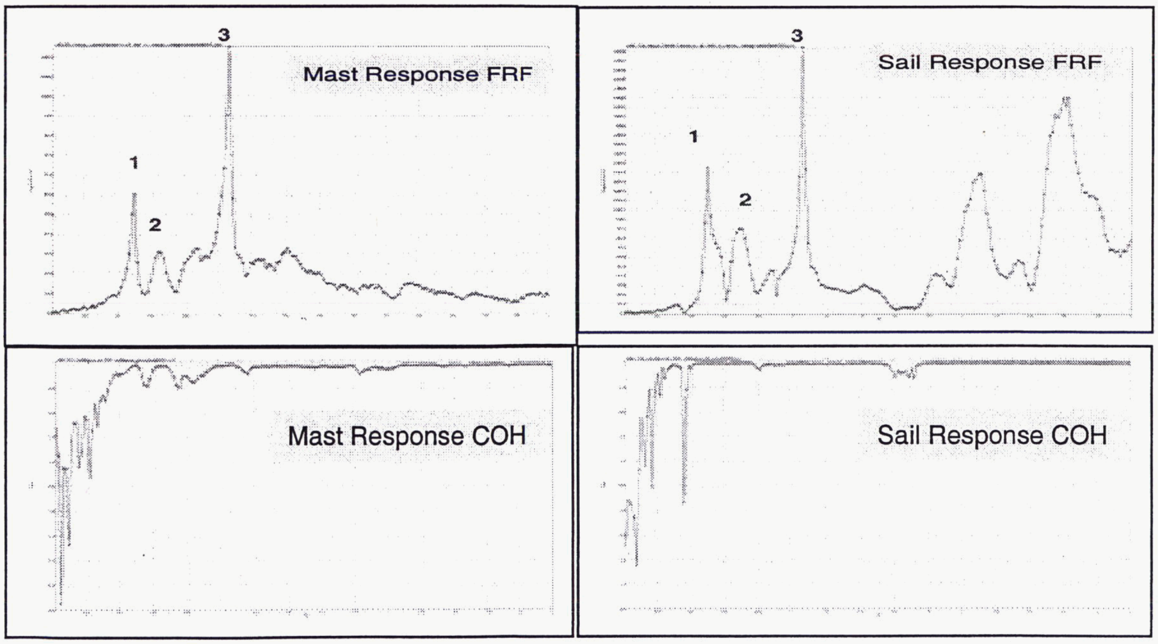

Figure 12. Sail Response In-Vacuum due to Piezo Stack Excitation at Mast Root

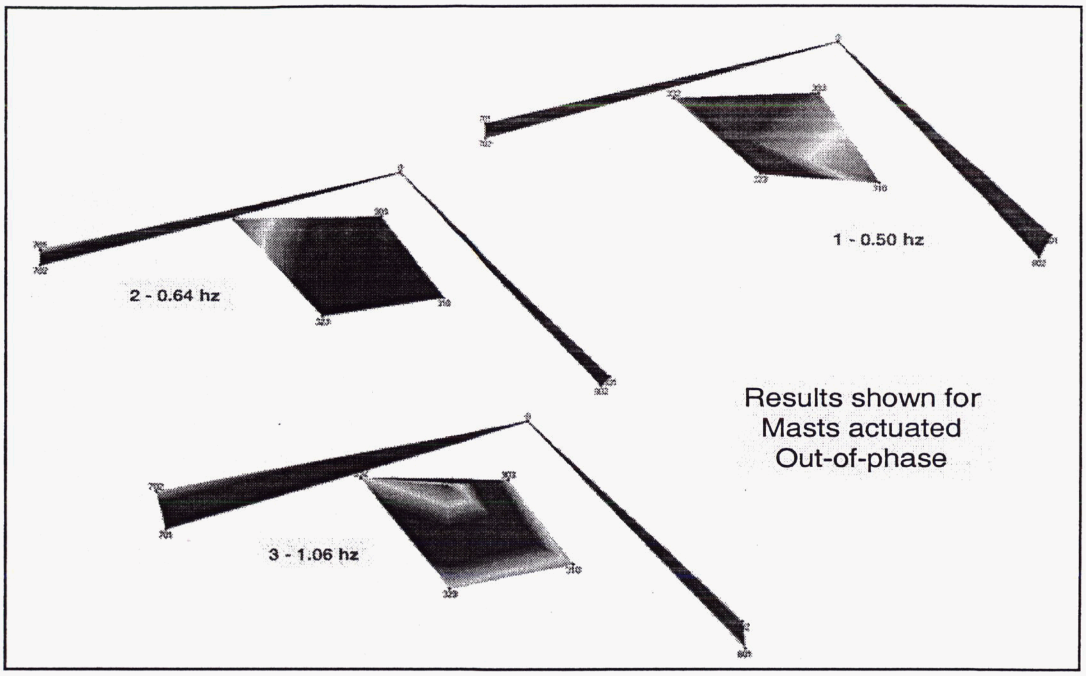

Figure 13. Sail ODS Modes due to Piezo Stack Excitation at Mast Root

Next the spreader bar (see Figure 14) excitation method was evaluated. This was done by driving one spreader bar for quadrant 3 with a sine sweep motion of various amplitudes. For these tests the spreader bar configuration was set at 22.5 degrees and required an eccentrically mounted mass to off-load the sail weight from the spreader bar. This eccentrically mounted mass interfered with the test objectives of evaluating how well the modal dynamics could be excited, as it caused a major swinging motion at the mast tip and interfered with the smooth sine sweep motion we were attempting to achieve. The tests did show that a significant motion of the system with spreader bar rotation is possible, but an improved setup would be required to properly evaluate system modal dynamics. However, it was felt that this technique would provide similar excitation capability to that found with the magnets and should be able to capture similar modes to those found with the magnetic exciters mounted at the halyard corners. Concerns about free-play and slop in the gears is still a concern and need further study.

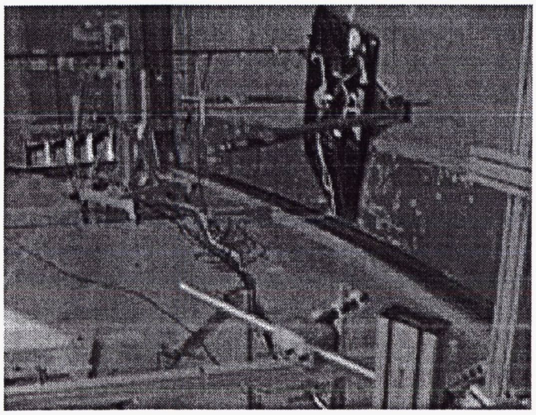

Figure 14. Spreader Bar at Mast Tip

The third technique evaluated was using a bi-morph MFC patch actuator to provide out-of-plane excitation at various positions on the cord of quadrant 3. This technique was successfully demonstrated on a 10-m sail. This technique has advantages over the other methods, in that it is the only one that allows for the actuators to be strategically positioned anywhere along the sail cord for exciting just about any mode desired. This is a very attractive capability, for as was demonstrated earlier the magnets at the halyards could not properly capture 2^{nd} and 3^{rd} order bending modes along the quadrant hypotenuse "long cord". This limitation would also apply to a fully functioning spreader bar exciter methodology. However, it was found during the 20-m system tests with the MFC's that the 6 lbs. cord load severely restricted the actuation performance, and that a redesigned actuator properly sized for this higher loading condition would be required to get good excitation. On a flight test program, studies should be conducted to optimize the MFC size for the loading conditions expected if this excitation method is used. Sail cord loading is significantly less (~0.5 lbs.) in a true on-orbit flight configuration that is free of gravity, so it is fairly simple to size the bi-morph MFC concept for this condition.

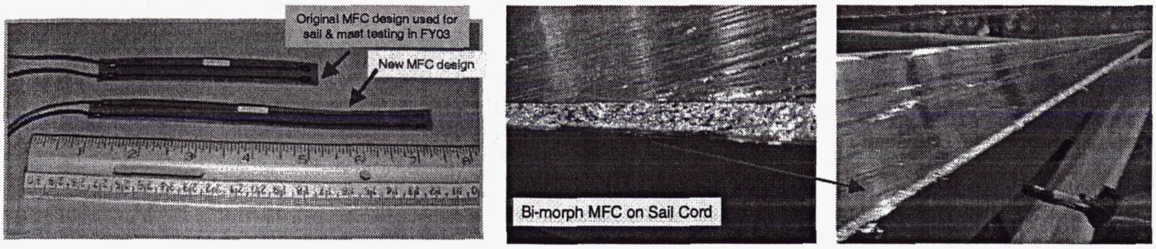

Figure 15. MFC Piezo Patch Actuator on Sail Cord

SUMMARY AND CONCLUSIONS

The 20-meter solar sail dynamics test program performed at the Plum Brook vacuum chamber facility was successfully completed with all test requirements met on time and schedule. Most importantly, the fundamental sail system modes needed for model correlation activity were identified with high confidence. In addition, higher order sail membrane modes were identified through a combination of many tests on each quadrant. The mast fundamental modes, critical for model correlation, were also identified using an innovative excitation technique suitable for flight-testing. Also, various excitation techniques were evaluated for in-vacuum dynamic tests. These techniques were shown to have promise, and recommendations for further study are made for incorporation into future test programs.

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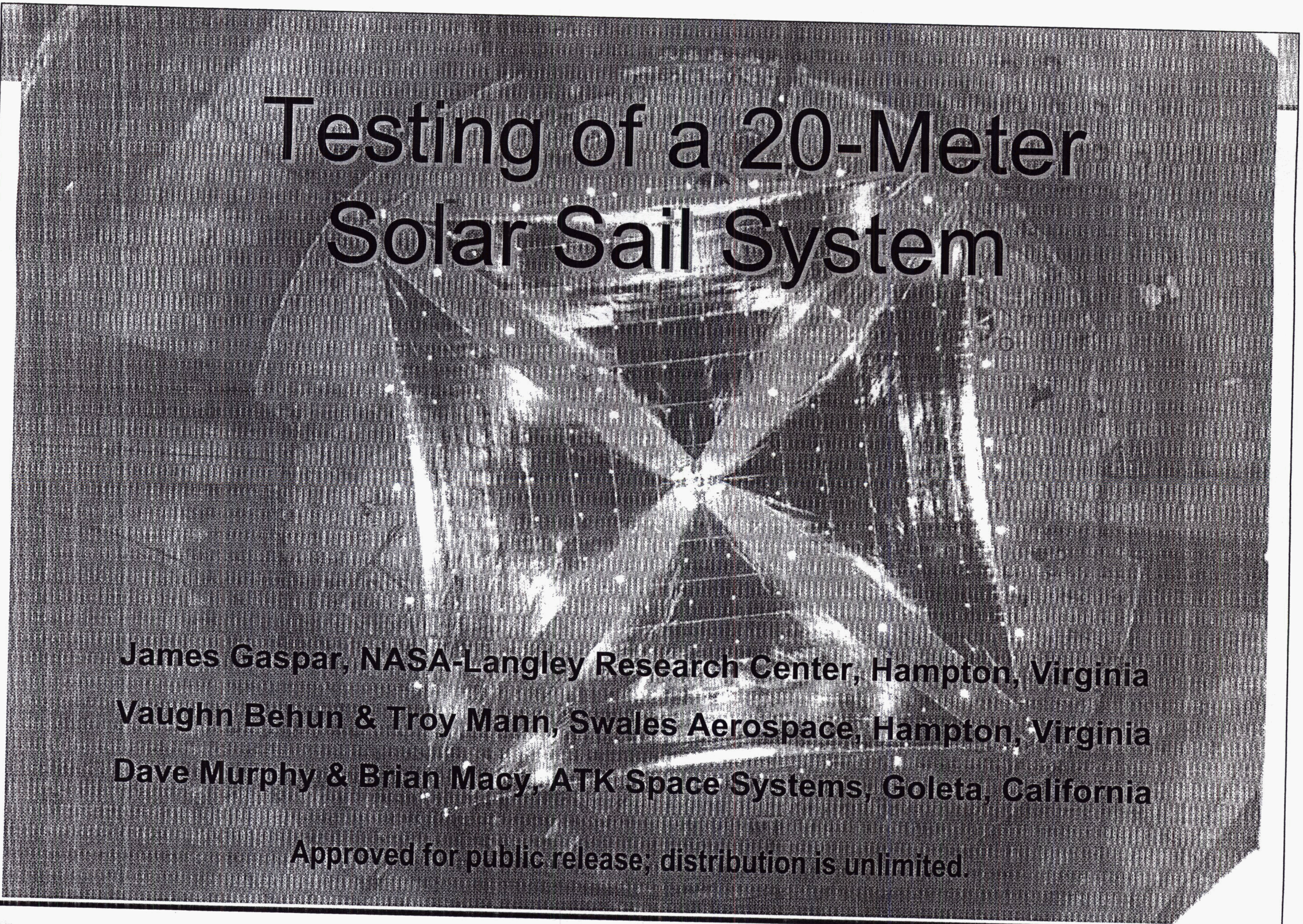

Testing of a 20-Meter Solar Sail System

James Gaspar, NASA-Langley Research Center, Hampton, Virginia

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Dave Murphy & Brian Macy, ATK Space Systems, Goleta, California

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Solar Sail Program

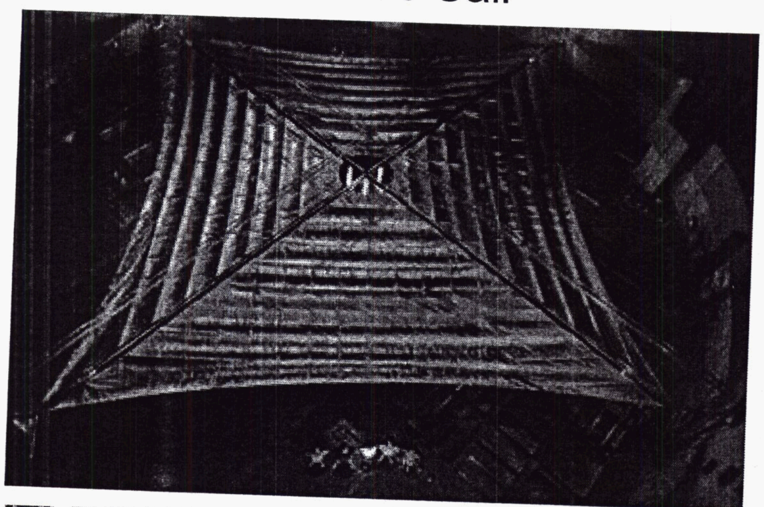
Overview

- NASA's In-Space Propulsion (ISP) Program has selected teams led by ATK Space Systems and L'Garde to develop scaled model solar sail hardware over the past three years, and to demonstrate its functionality on the ground
- Both are 4-quadrant, square sail designs with four lightweight booms (linear density < 100 g/m^2) and ultra-thin membrane (areal density < 10 g/m^2)

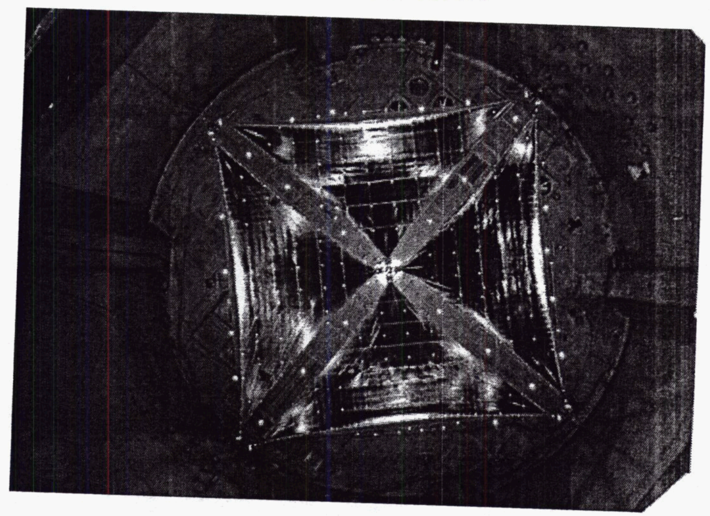
How it works

- Solar Sail's use the Sun's energy to travel through space, much the way wind pushes sailboats across water. The technology bounces photons off giant, reflective sail membranes
- The continuous pressure provides thrust for maneuvering, hovering, rotation of plane of orbit
- Requires NO onboard propellant, thus significant payload mass reduction

L'Garde Sail



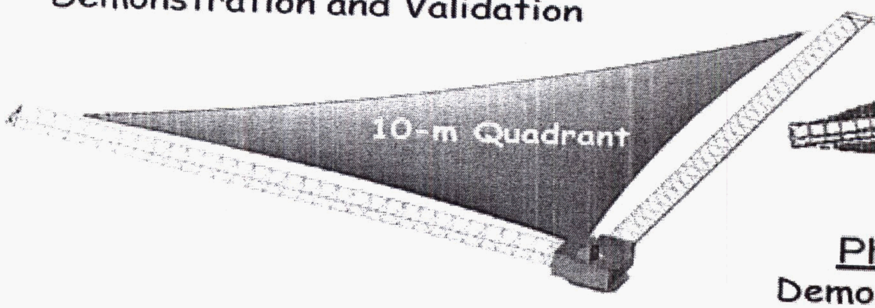
ATK Sail

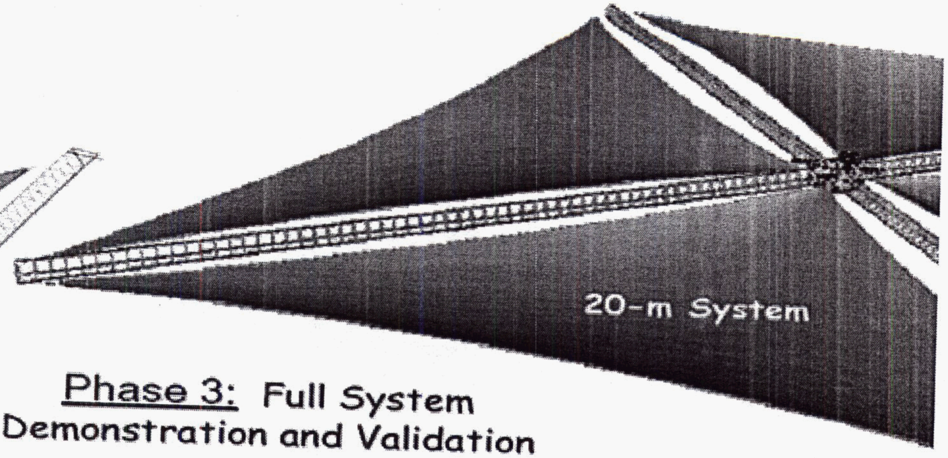


NASA-ISP Sail Program Overview

- Conduct solar sail development and demonstration activities in three phases to increase TRL of a scalable solar sail ***system***
  - Program Phases:
    - ✓ Concept Refinement (CR) — 6 months — 12-02 to 6-03
    - ✓ Hardware Development (HD) — 13 ½ months — 6-03 to 7-04
    - ➢ System Demonstration (SD) — 1 year — 7-04 to 7-05

<u>Phase 2:</u> Hardware Development and 1/4 Symmetry System Demonstration and Validation





<u>Phase 3:</u> Full System Demonstration and Validation

SOLAR SAIL DYNAMICS TEST - Introduction

Objective

- Measure sail system dynamics for analytical model correlation in relevant environment

Sail System Test Setup

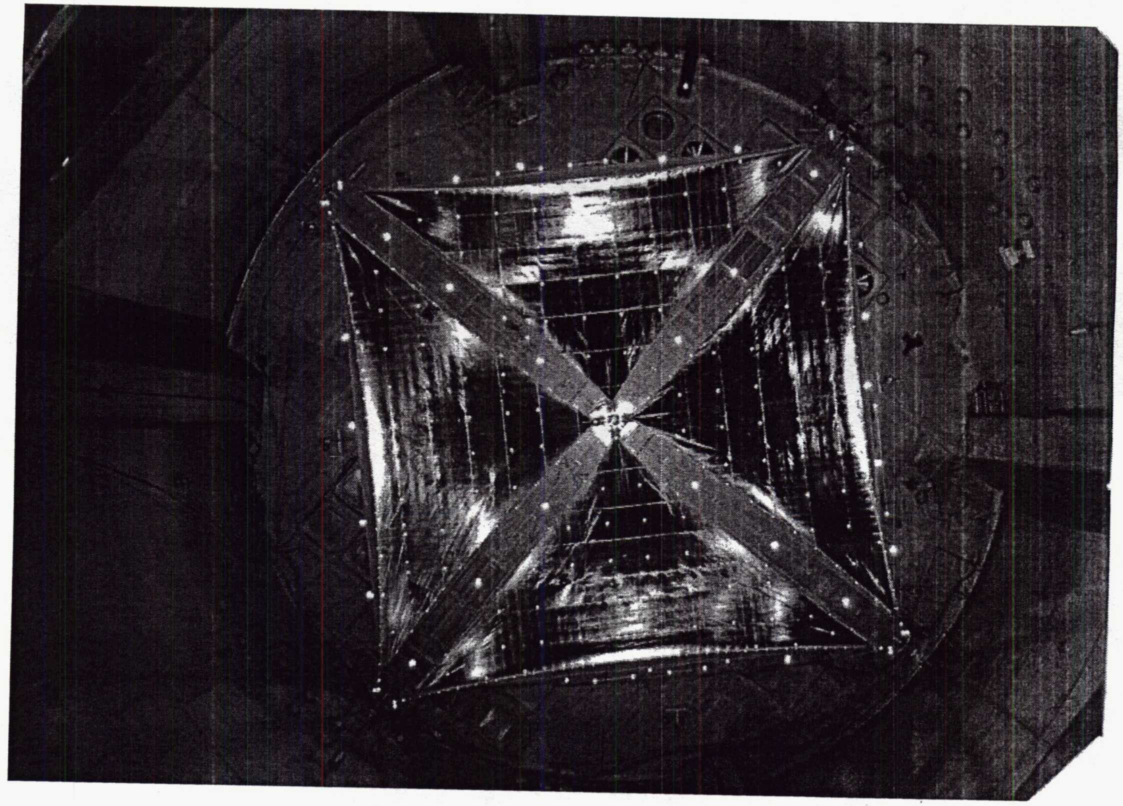
- Mast tips off-loaded with negator springs
- 44 targets on each sail quadrant
- Magnetic exciters for sail system
- 1 Torr vacuum environment

Mast Test Setup

- Mast tips off-loaded with cable (model simulates condition)
- 3 targets at each mast tip (lateral, longitudinal, torsion)
- Piezo stack exciter at mast root
- Ambient environment

Instrumentation

- Laser Vibrometry



20-meter Solar Sail System

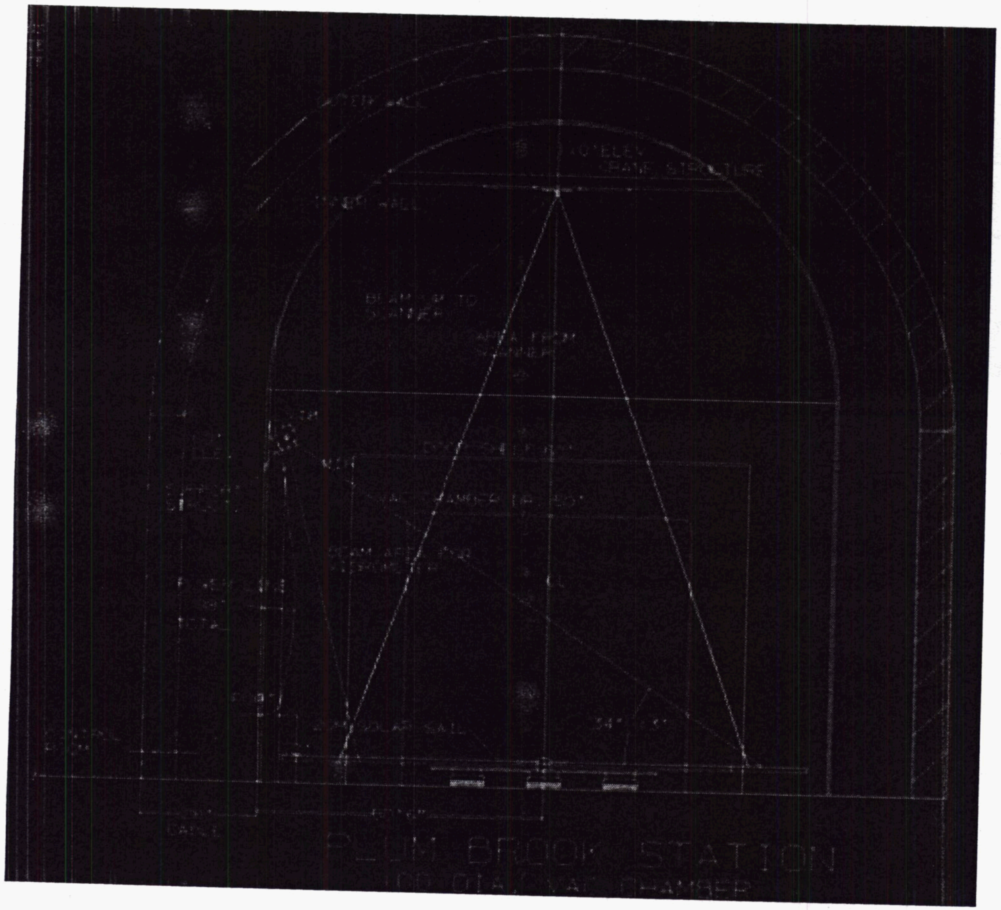
Success Criterion

- Measure **sail system** fundamental modes in relevant environment
  - Three fundamental modes
- Measure mast modal dynamics
  - 1^{st} lateral bending, 1^{st} longitudinal bending, and 1^{st} torsional dynamics

Why In-Vacuum Testing?

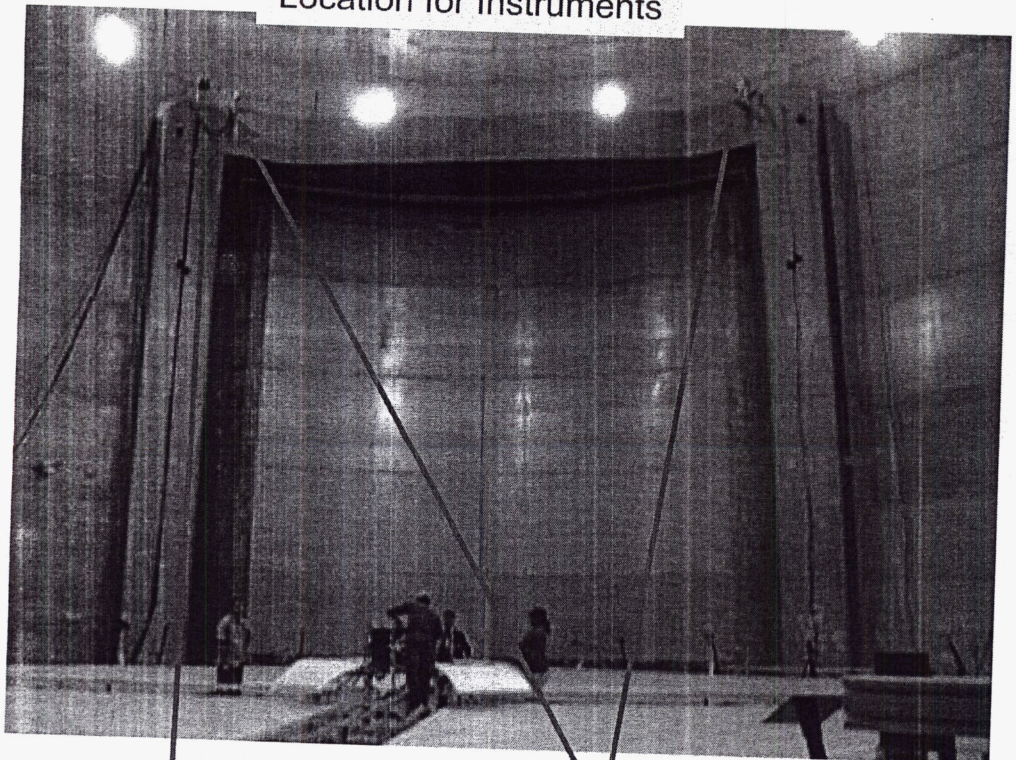
- Mass loading effects from atmosphere are significant with thin membranes
  - Mass of air surrounding membrane is an order of magnitude greater than the membrane mass itself
  - Convective air motion is significant disturbance to sail dynamics
- Advance Sail modeling for accurate predictions of flight hardware
  - Sail shape, center of pressure, sail strain, sail thrust and moment, sail frequencies and mode shapes, static boom shape, boom loading, boom frequencies and mode shapes, temperature
- Significant Challenges for structural prediction
  - Large planform (> 50 m), extreme thinness of the sail membranes (< 2 microns), low initial sail stress (< 7 kPa)

Vibrometry Measurement System Installation



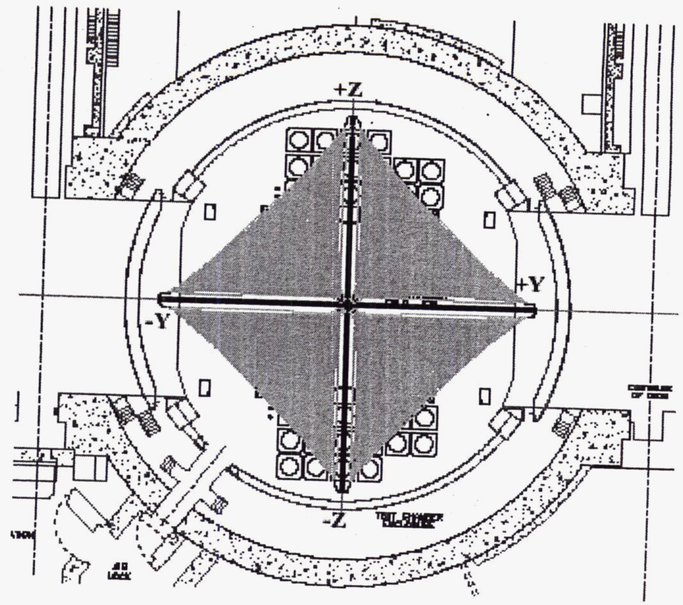
- Vibrometer on Door
  - Directs laser to SMS on crane
- SMS on Crane
  - Directs laser to test article
  - +/- 20 degree scan range captures entire test article
- System Performance
  - Target centering algorithm used to properly align laser onto SMS and test article
  - System validated to work at 260 feet range (well beyond 180 feet range for PB)
  - Dynamics obtained with built in interferometry capability
  - 1st time installation (not used during L-Garde Phase 2)

Instrumentation in Plum Brook Vacuum Chamber



Instrumentation on Door Ledge

- 4 Photogrammetry canisters
  2 per door ledge
- 1 Vibrometer canister

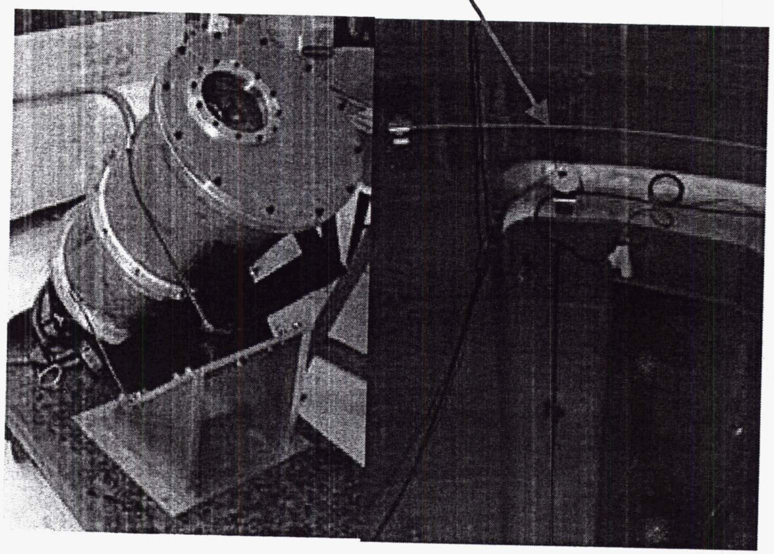


SAIL SYSTEM DYNAMICS - Instrumentation

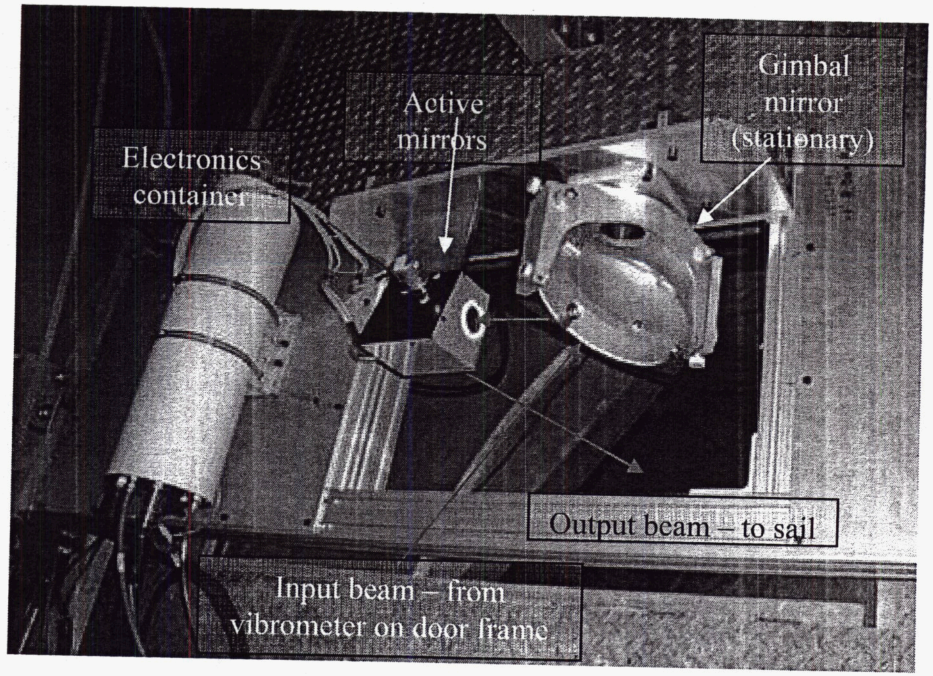
Instrumentation for vibrometry

- Scanning laser vibrometer is mounted on door frame pointed toward Scanning Mirror System (SMS) on crane
- SMS redirects laser to sail surface for velocity measurements

Vibrometer on door frame



Scanning Mirror System on crane

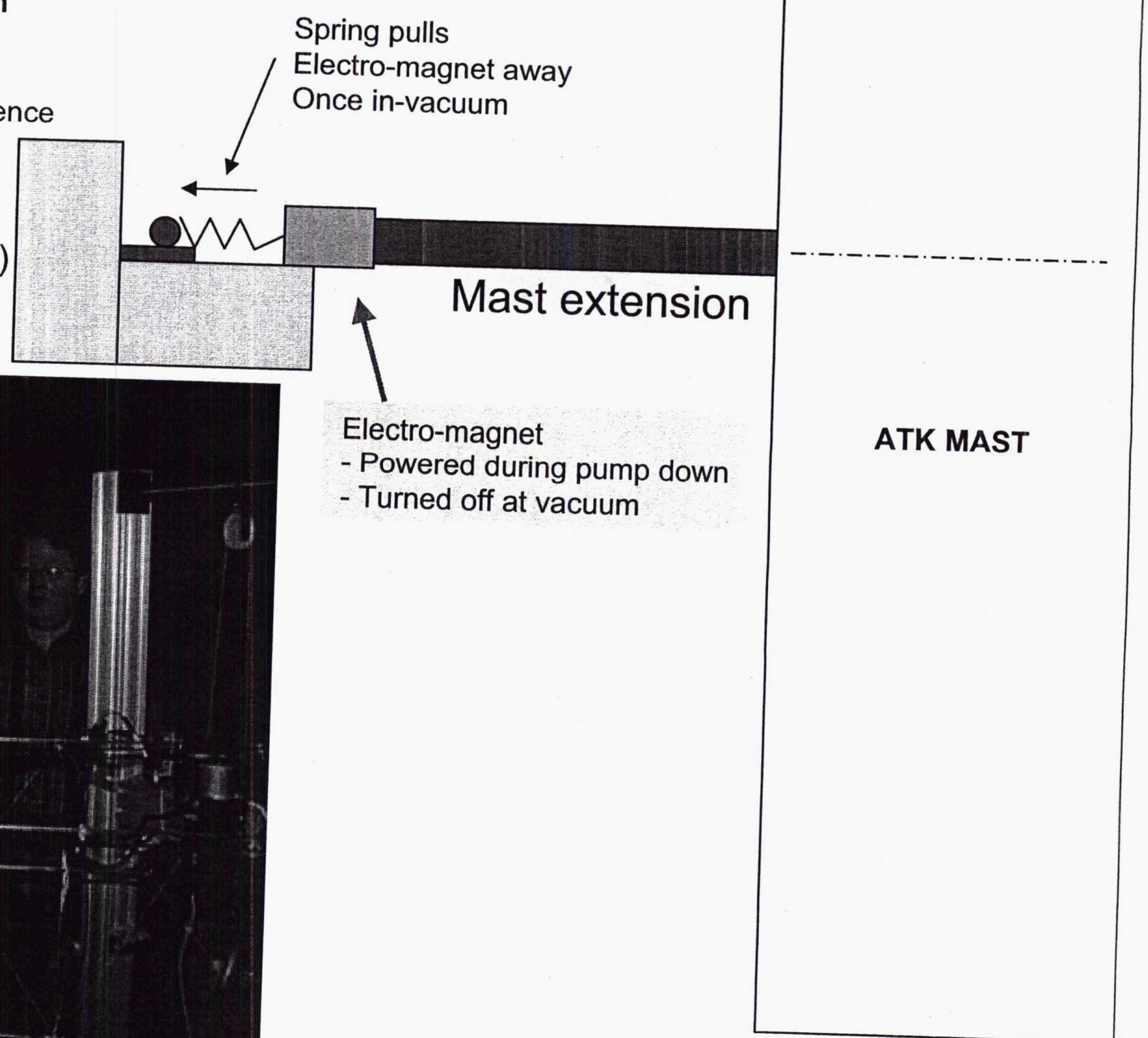


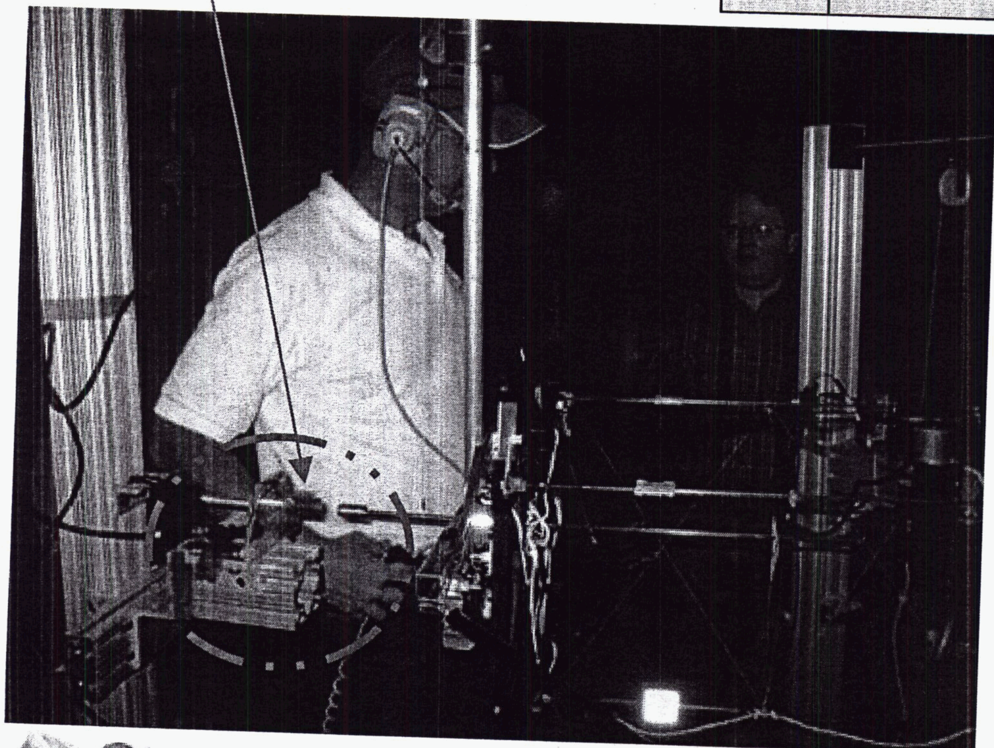
Scanning Mirror System mounted on the Polar Crane

Mast Tips Held Stationary During Vacuum Pump Down

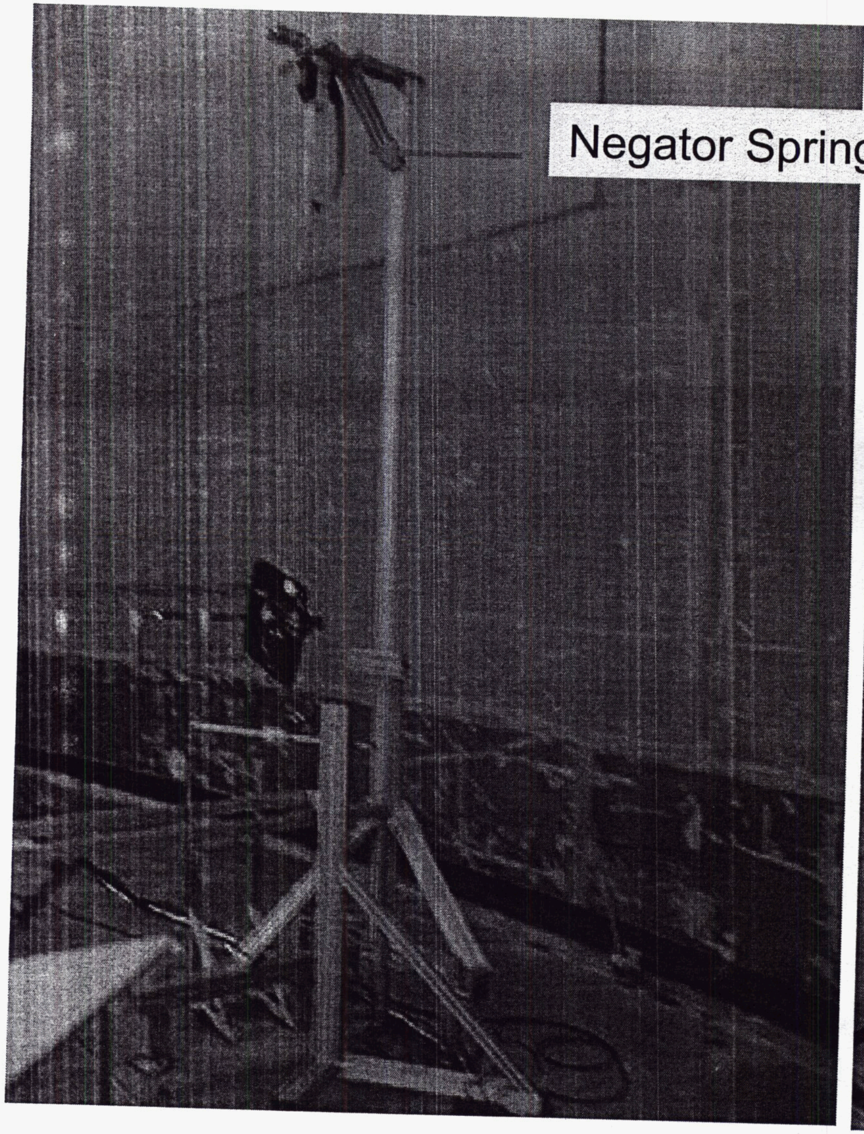
Magnet holds mast tip during pump down

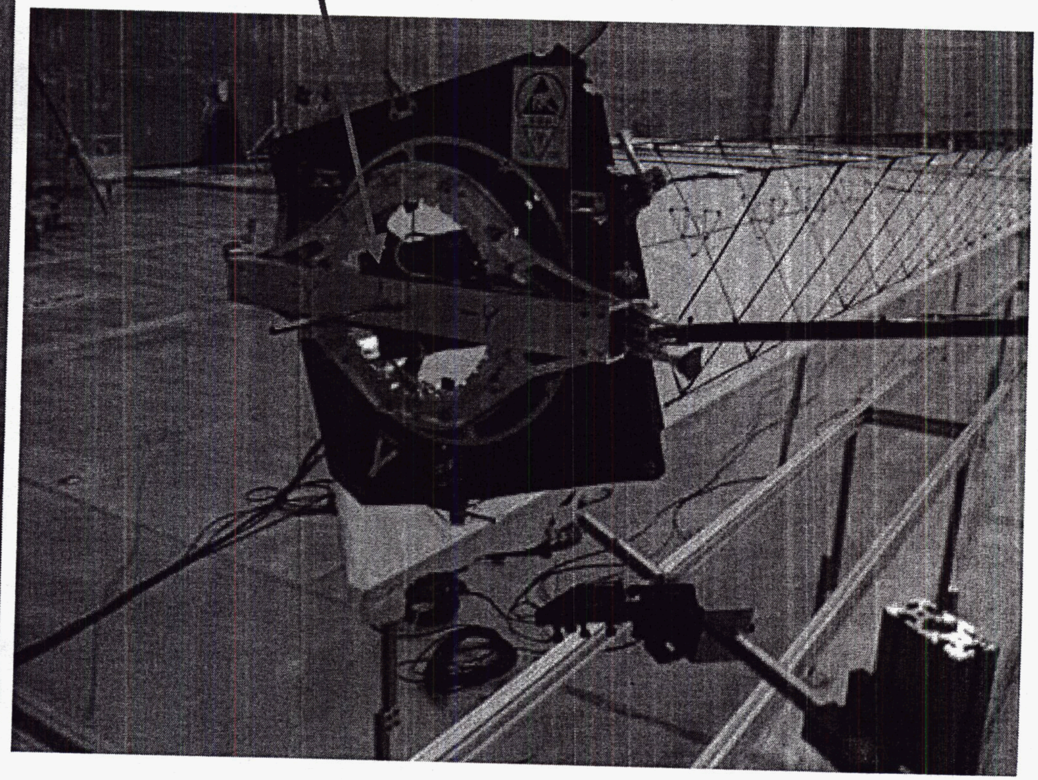
- Once at vacuum, power removed to free mast tip
- Dynamic Testing can then commence





Mast Tips Off-loaded with Negator Spring during System Dynamics

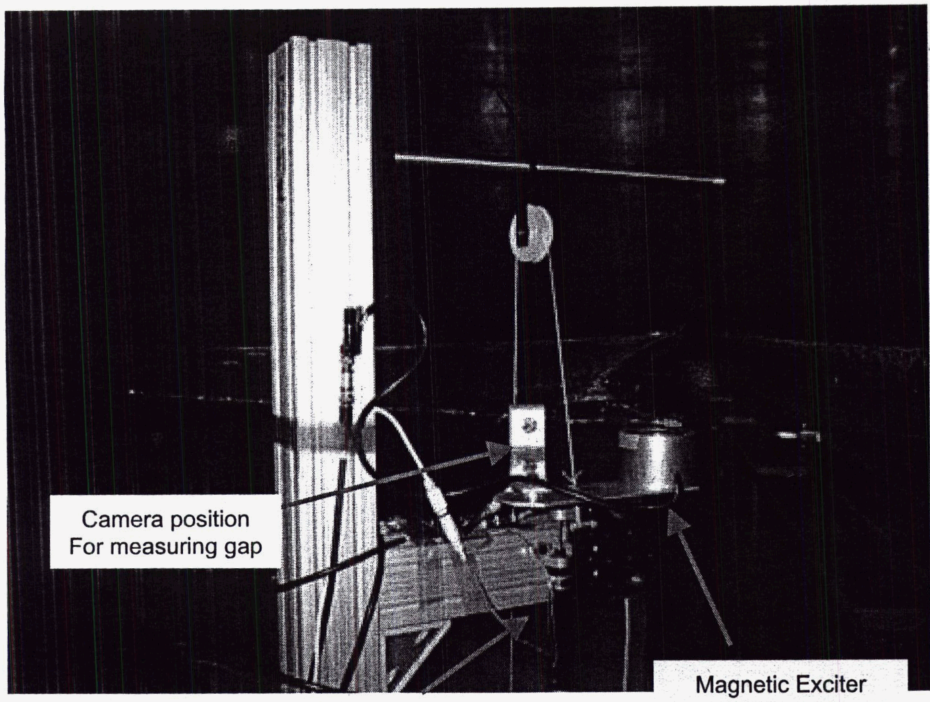




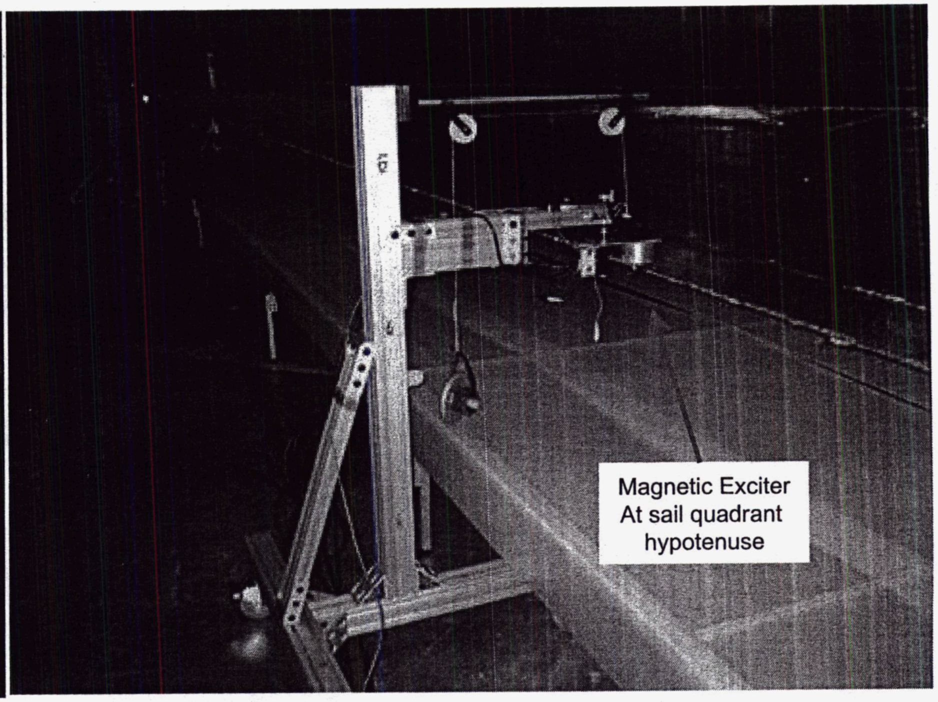
Baseline Sail Dynamics Method – Validated on 10-m Quadrant

MAGNETIC EXCITER SYSTEM CONFIGURATION

- 1 magnetic exciter mounted at each sail quadrant corner (12 total)
- 1 magnetic exciter mounted at each sail quadrant hypotenuse (4 total)
- Cameras used to validate proper spacing between magnet & sail in-vacuum
  - at halyards & quadrant hypotenuse exciter locations (12 total)
  - ~5mm gap for optimum performance
  - Scale used in camera field-of-view on magnet to determine gap
- Linear actuators used to precisely adjust gap between magnet & sail
  - At halyards & quadrant hypotenuse exciter locations (12 total)



Linear Actuator



Sail Dynamic Tests Completed at Plum Brook - Summary

System Tests with 0 Degree Spreader Bar (Sail Halyard Magnetic Excitation) – Vacuum

#	Test Name	Meas. #	Explanation
1	Q4M1M2 - Mast Tips Fixed	11	Check-out techniques while mast tips are fixed with magnetic restraint
2	Q4M1 - Mast Tips Fixed	7	Check-out techniques while mast tips are fixed with magnetic restraint
3	Q4M1 - Test DC offset method – Tips Free	13	Check-out techniques with mast tips free to float on soft suspension system
3	Q4M1M2 – Test DC offset method – Tips Free	13	Check-out techniques with mast tips free to float on soft suspension system
4	**Q4M1M2 – Sail Quad**	**44**	**1st baseline test on Quad 4 with M1 & M2 excitation out-of-phase**
5	**Q4M1 – Sail Quad**	**44**	**2nd baseline test on Quad 4 with M1 excitation**
6	**Q4M2 – Sail Quad**	**44**	**3rd baseline test on Quad 4 with M2 excitation**
7	Q3M1M2 – Sail Quad	15	1st baseline test on Quad 3 with M1 & M2 excitation out-of-phase
8	Q3M1 – Sail Quad	15	2nd baseline test on Quad 3 with M1 excitation
9	Q1M1M2 – Sail Quad	15	Only baseline test on Quad 1 with M1 & M2 excitation out-of-phase
10	Q2M1M2 – Sail Quad	13	Only baseline test on Quad 2 with M1 & M2 excitation out-of-phase
12	**Full Sail System – All Quads with M1**	**28**	**Only baseline test on Full Sail System with M1 excitation on each Quad in-phase**

System Tests with 0 Degree Spreader Bar (Validate Excitation Techniques) – Vacuum

#	Test Name	Meas. #	Explanation
1	Q3 Dual Mast in-phase	9	Validation test on Quad 3 with dual mast in-phase excitation via piezo's at root
2	Q3 Dual Mast out-of-phase	9	Validation test on Quad 3 with dual mast out-of-phase excitation via piezo's at root

Sail Dynamic Tests Completed at Plum Brook - Summary

- 2nd Chamber pump down required for 22.5 Degree Spreader Bar Tests
  - Required to setup hardware for new sail configuration & properly align system
  - Install counter balance weights at mast tips (gravity off-loading)
  - Install MFC piezo patches on Quad 3 cord

System Tests with 22.5 Degree Spreader Bar (Sail Halyard Magnetic Excitation) – Vacuum

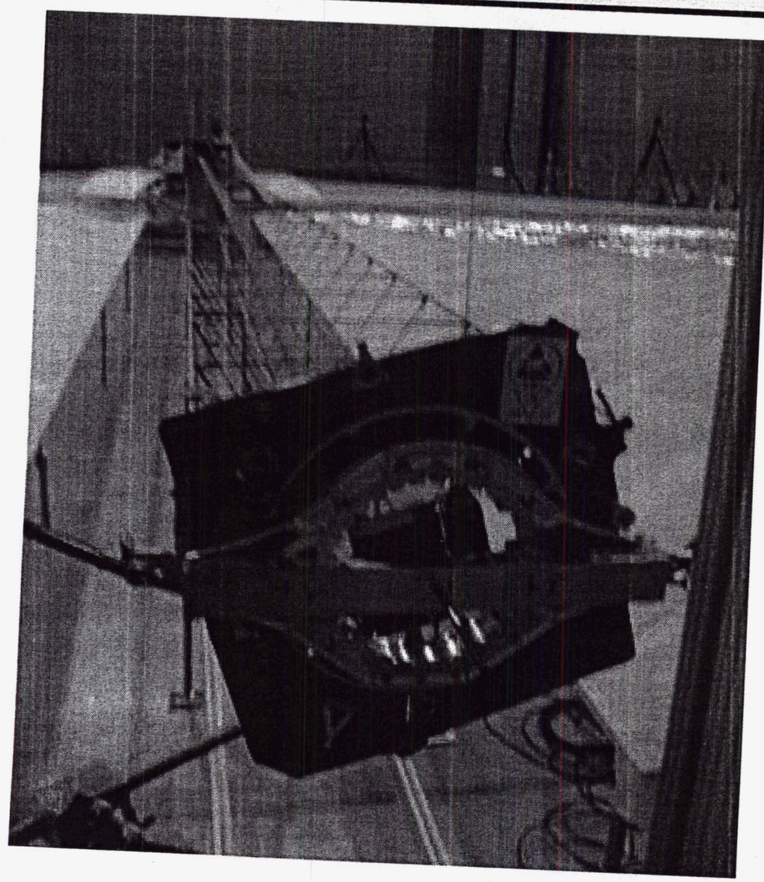
#	Test Name	Meas. #	Explanation
1	Q4M1M2 – Sail Quad	13	1st baseline test on Quad 4 with M1 & M2 excitation out-of-phase
2	Q3M1 – Sail Quad	44	1st baseline test on Quad 3 with M1 excitation
3	Q3M3 – Sail Quad	13	1st baseline test on Quad 3 with M3 excitation near tack-line
4	Q3M1 – Sail Quad @ Three Pressures	3	Sail response at 1, 10, and 100 Torr. Use to research influence of air on sail dynamics

System Tests with 22.5 Degree Spreader Bar (Validate Excitation Techniques) – Vacuum

#	Test Name	Meas. #	Explanation
1	Q3 Sail Response - Mast Excitation via Piezo Stack at Root	35	Numerous single point measurements and small scans to assess the capability of sail excitation via piezo stack actuators at mast root. Assess sail response due to single mast, dual mast in-phase, and dual mast out-of-phase excitation.
2	Q3 Sail Response – Spreader Bar Excitation at Mast Tip	3	Numerous single point measurements to assess the capability of sail excitation via spreader bar rotation at the mast tips.
3	Q3 MFC Patch Excitation on Sail Cord	--	Validation test on Quad 3 with MFC excitation on cord of sail

Sail Dynamic Tests Completed at Plum Brook - Summary

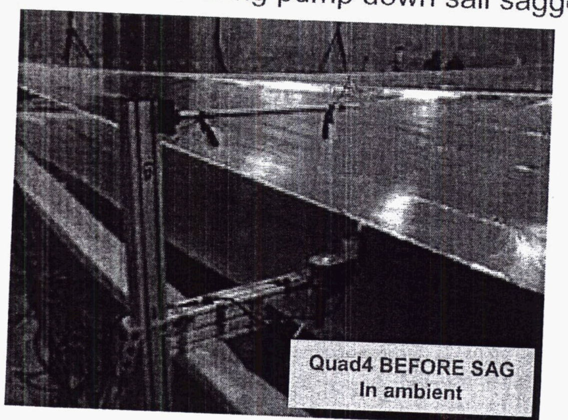
Mast Tests with Sail Detached (Piezo Excitation at Root) – Ambient			
#	Test Name	Meas. #	Explanation
1	Mast Tests	3 per mast	Each mast dynamically tested using piezo excitation at the root to get fundamental mast modes in ambient



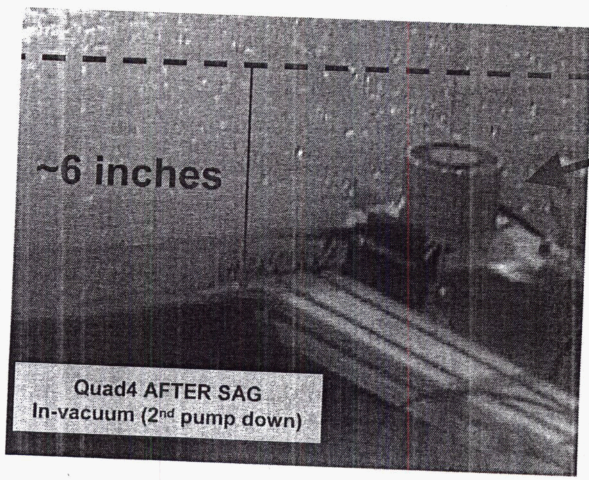
20-m Sail Dynamics In-Vacuum – Test Results Summary

Data Quality Concerns - System Tests with 22.5 Degree Spreader Bar (2nd Chamber Pump Down)

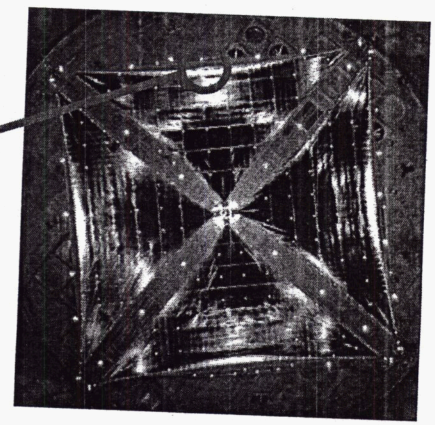
- During chamber pump down sail quadrants sagged over 6 inches at center of long cord
  - Plum Brooks chamber produces a large moisture build up (FOG) during pump down
  - Moisture build up added weight to sail which caused the halyard negators to pay out the long cord
  - Sail became lodged under magnetic exciters positioned at center region of long cord
  - Quads 1 & 2 were obviously grounded
  - Quads 3 & 4 are believed to be somewhat grounded after data evaluation
  - Data quality of all the dynamics data from the 2nd chamber pump down is suspect
- Sail sag identified during 1st chamber pump down when it sagged ~3 inches at center of long cord
  - Only impact to testing was the magnetic exciters positioned above the center of the long cord were rendered useless as they were too far from the sail to be effective
  - All halyard exciters still useful
  - No data quality concerns for any dynamics data from 1st chamber pump down due to this issue
- Corrective measure for 2nd chamber pump down did not work
  - Knowing the sail could sag at least 3 inches the magnetic exciters were positioned 3 inches below the sail
  - Expected sail to sag within range of magnetic exciters (then linear actuator could fine tune gap for tests)
  - During pump down sail sagged BELOW magnetic exciters and became lodged underneath them for all quadrants



Quad4 BEFORE SAG
In ambient



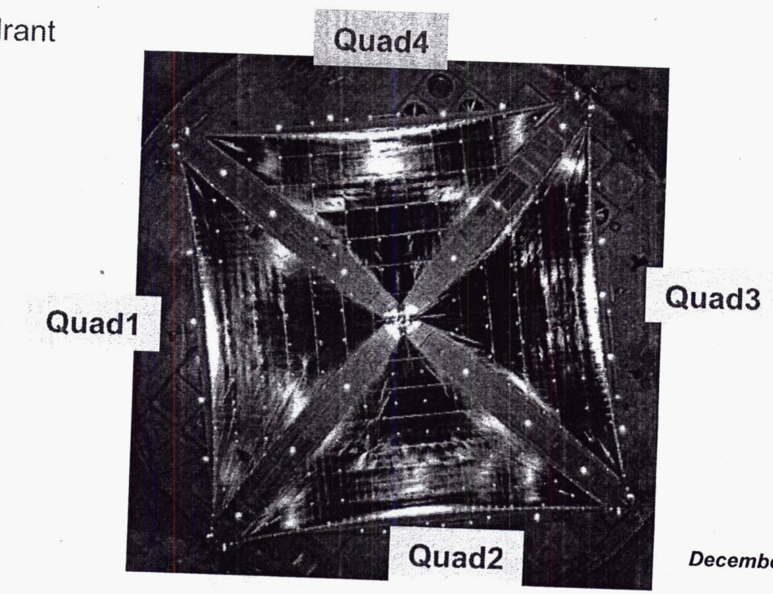
Quad4 AFTER SAG
In-vacuum (2nd pump down)



Sail Dynamic Tests Completed at Plum Brook – Test Results Summary

Dynamic Test Data Analysis Completed – System Tests with 0 Degree Spreader Bar Angle (1st Chamber Pump Down)

- Major Focus on Quadrant 4 results (44 measurement points per test)
  - Highest grade sail that is most flight like
  - Quadrant dynamic results analyzed from Q4M1, Q4M2, and Q4M1M2 tests
  - Dominant modes identified and assessed for quality
- Quadrant 3 (15 measurement points per test)
  - Quadrant dynamic results analyzed from Q3M1 and Q3M1M2 tests
  - Dominant modes identified and assessed for quality
- Quadrants 1 and 2 ($15_{(Q1)}$ & $13_{(Q2)}$ measurement points per test)
  - Reduced interest in data as Quadrant 2 had a major tear and Quadrant 1 had many previous repairs
  - Quadrant dynamic results analyzed from Q1M1M2 and Q2M1M2 tests
- Full Sail System with each Quadrant Excited by M1 Magnet's Simultaneously (all 4 exciters driven in-phase)
  - Important for determining system level modes and mast participation with sail
  - Compared with quadrant tests to determine detailed sail dynamics at each system level mode
  - 2 Mast tip measurements for each mast
  - 5 Sail membrane measurements for each quadrant
- Ambient Mast Dynamics with Sail Detached
  - Identify dominant mast modes

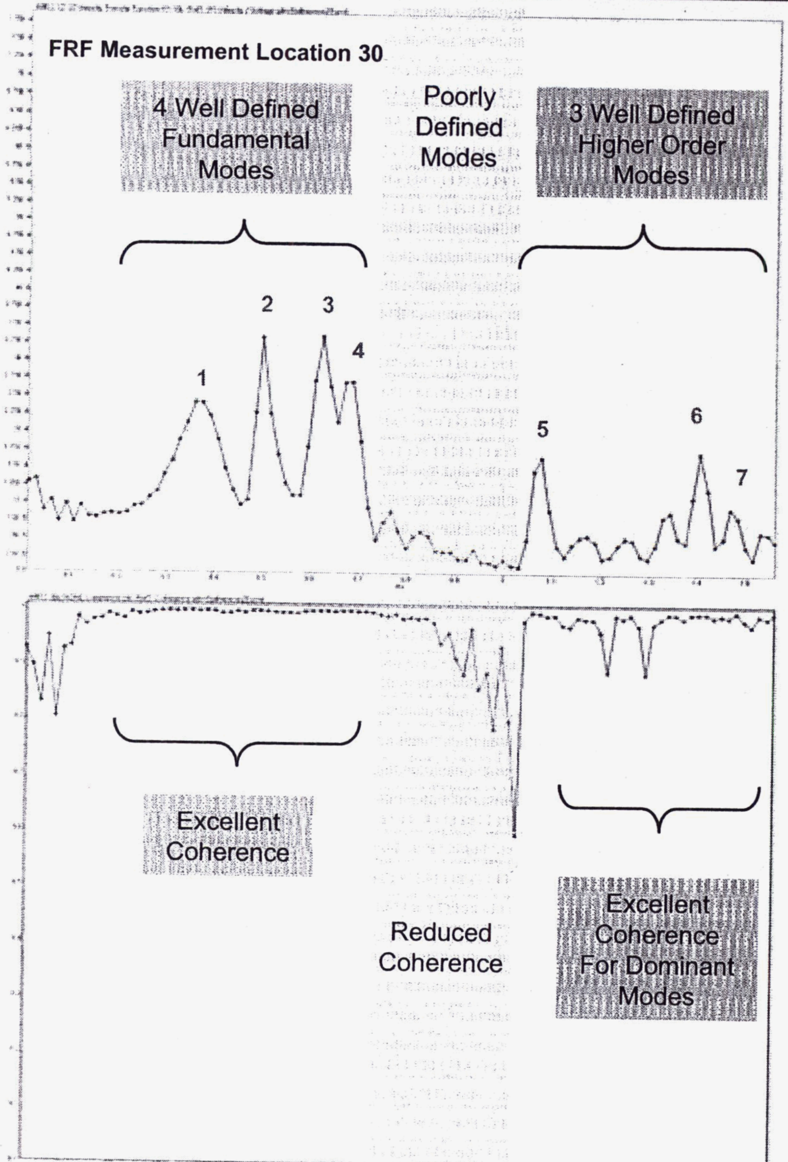


20-m Sail Dynamics In-Vacuum – Quads 4 & 3 Mode Identification Results

- Dominant first five mode frequencies highlighted in RED repeat for all tests

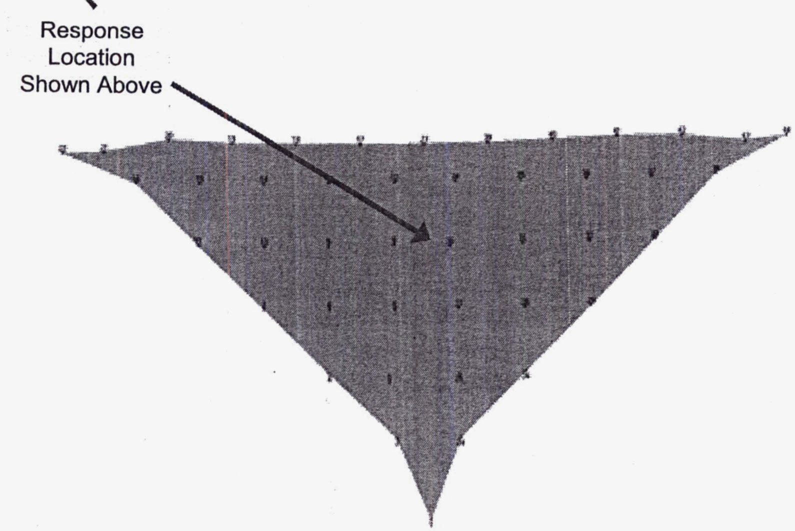
Row #	Q4M1		Q4M2		Q4M1M2		Q3M1		Q3M1M2	
	Hz	Rating	Hz	Rating	Hz	Rating	Hz	Rating	Hz	Rating
1	0.375	1	0.391	1	0.359	1	0.406	1	0.406	1
2	0.500	1	0.500	1	0.500	1	0.500	1	0.500	1
3	0.625	1-	0.531	2	0.625	1-	0.625	1	0.625	1
4	0.687	2+	0.625	1-	0.672	2+	0.703	1-	0.688	1-
5	1.06	1	0.687	1	0.937	2+	0.766	2+	0.766	2+
6	1.34	2	0.766	1-	1.0	2	0.828	2+	0.828	2
7	1.41	1-	0.828	2+	1.06	1	0.891	2	0.891	2-
8	1.47	2+	0.906	1-	1.34	2	0.938	2-	0.953	2-
9	1.80	2-	0.937	2+	1.41	1-	1.06	2+	1.00	2-
10	1.84	2-	1.0	2+	1.47	2+	1.14	2	1.06	2+
11	2.28	2-	1.06	1-	1.80	2-	1.27	2+	1.14	2
12	2.33	2	1.34	2+	1.84	2-	1.33	2	1.19	3
13	2.41	2-	1.41	1-	2.33	2	1.41	2	1.27	2+
14	2.48	2-	1.47	2+	2.52	2	1.47	2	1.33	2
15	2.52	2	1.55	2	2.80	2	1.55	2-	1.41	2
16	2.78	2	1.59	2			1.59	3	1.47	2
17			1.80	2-			1.66	3	1.53	2-
18			1.84	2-			1.95	3	1.59	3

20-m Sail Dynamics In-Vacuum – Quad4 (Q4M1) FRF & Coherence Results



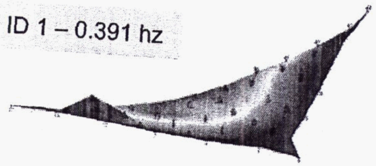
Seven Dominant Modes Below 2 Hz

- FRF's & Coherences Look Good for the Dominant Modes
  - FRF peaks well defined
  - Excellent Coherence at resonance
- Excellent repeatability
  - Dominant peaks repeat test-to-test
  - Repeated for all 3 tests on Quad 4
  - Repeated for both tests on Quad 3

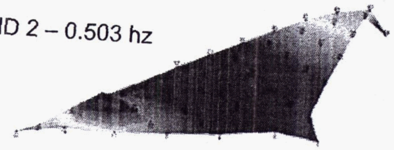


20-m Sail Dynamics In-Vacuum – Overall Test Mode Summary

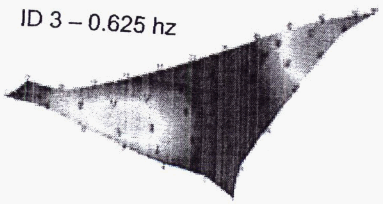
ID 1 – 0.391 hz



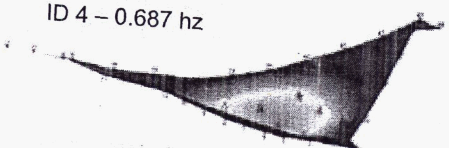
ID 2 – 0.503 hz



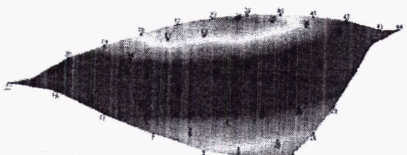
ID 3 – 0.625 hz



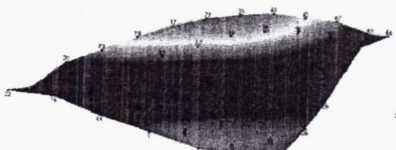
ID 4 – 0.687 hz



ID 5 – 0.937 hz

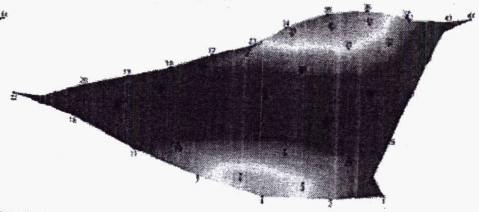


ID 6 – 1.0 hz

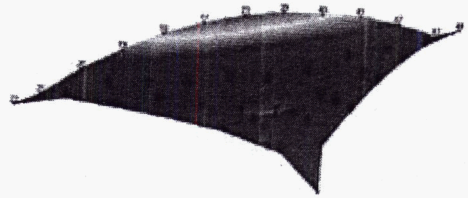


ID #	SUMMARY of DOMINANT ODS MODES				
	ODS #	Hz	Rating	Description	Notes
1	1	0.391	1	Sail Vertical Motion / Heavily Damped Non-linear Mechanism Mode	Potentially related to negator springs in halyard and/or on mast tip
2	2	0.503	1	**Sail System 1st Mode "Pin Wheel Mode"** Sail Rocking / All Mast Tips Twist in-phase	Mast Dominant Mode, sail follows
3	3	0.625	1-	Sail Rocking / Y Tips OOP / Z Tips OOP	Mast Dominant Mode, sail follows
4	4	0.687	2+	**Sail Membrane 1st Breathing Mode** Long Cord 1st Bending / Centerline 1st Bending	Membrane Mode, 1st centerline
5	8	0.937	2+	Long Cord 1st Bending / Centerline 2nd Bending (1)	Membrane Mode, 2nd centerline
6	9	1.0	2+	Long Cord 1st Bending / Centerline 2nd Bending (2)	Membrane Mode, 2nd centerline
7	5	1.06	1	Asymmetric Sail Mode LT Side Short Cord & RT Side Long Cord OOP	Mast Dominant Mode, sail flex, Full system response
8	6	1.41	1-	Long Cord 1st Bending / Centerline 3rd Bending (1)	Membrane Mode, 3rd centerline
9	7	1.47	2+	Long Cord 1st Bending / Centerline 3rd Bending (2)	Membrane Mode, 3rd centerline

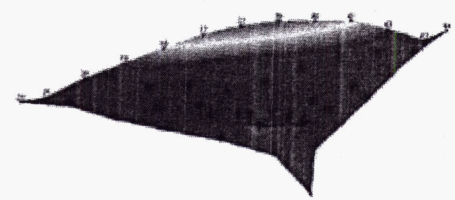
ID 7 – 1.06 hz



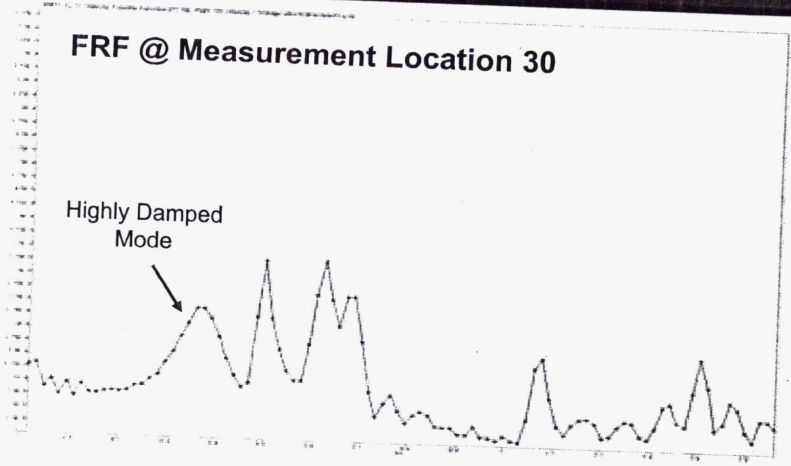
ID 8 – 1.41 hz



ID 9 – 1.47 hz



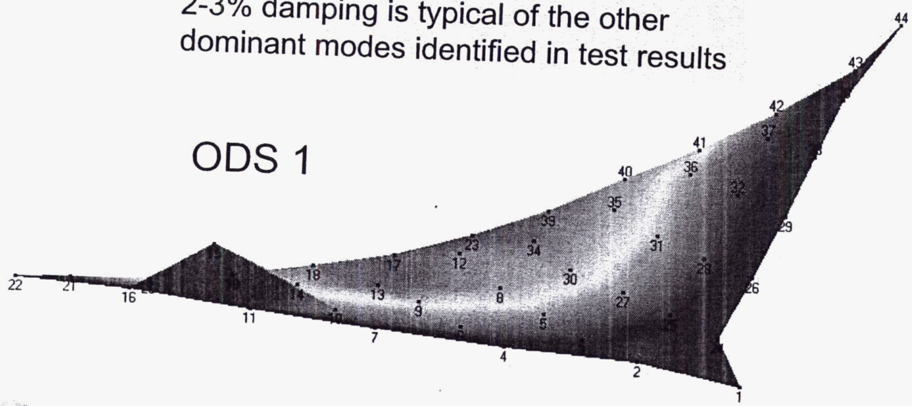
20-m Sail Dynamics In-Vacuum – Quad4 (Q4M2) Dominant Test Mode Shape Results



ODS #	Freq. (Hz)	Damping (%)	Mode Rating
1	0.391	19.9	1

Dominant Heavily Damped Mode:
2-3% damping is typical of the other dominant modes identified in test results

ODS 1



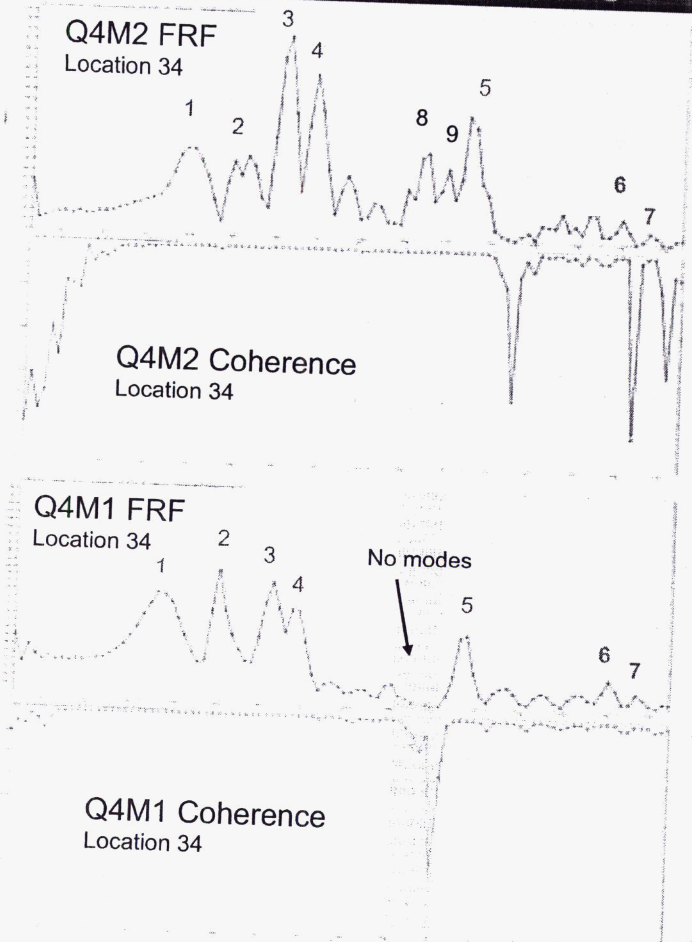
Dominant Heavily Damped Modes

- May not be a reliable structural mode
- Indicator of non-structural mechanism
- Potential non-linearity
  - Free-play
  - Sliding Friction

Explanation for High Damping

- ODS "1" is a non-linear mode
  - Non-linearity may be introduced through mechanism holding system or cord
  - Halyard negator springs were not locked during test which could potentially allow for cord sliding friction
  - Mast tip negator springs unlocked allows for mast tip vertical motion
  - Only dominant mode with some frequency variation test-to-test on Quad 4 further indicates non-linearity

20-m Sail Dynamics In-Vacuum – Important Quad4 Test Modes for Correlation
(Long Cord 1st Bending / Centerline 2nd Bending)

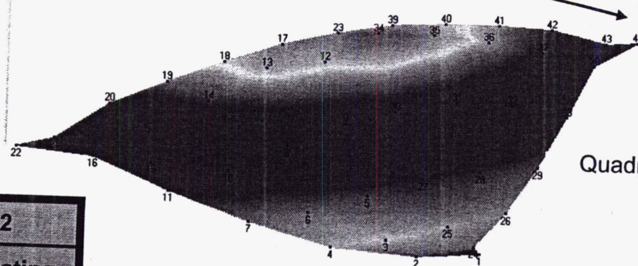


ODS #	Q4M1		Q4M2		Q4M1M2	
	Hz	Rating	Hz	Rating	Hz	Rating
8	--	--	0.937	2+	0.937	2+
9	--	--	1.0	2+	1.0	2

Important Fundamental Test Modes for Correlation

- Strong Modes from Q4M2 & Q4M1M2 Tests
  - Strong FRF response peaks with excellent coherence at resonance
  - Smooth symmetric mode shapes as expected
  - Mode shapes similar to those found in 10-meter Sail test at Langley
  - Mode shapes similar to pre-test analytic predictions
- Not Identified from Q4M1 Test
  - Difficult to excite from halyard corners
  - Exciter near a node-line for this mode shape
- Goal was to use exciter at quadrant hypotenuse for this mode
  - Significant sail sag (>3 inches) experienced going into vacuum
  - Sag shifted sail quadrant hypotenuse out of range for exciter
  - Limited to using only halyard magnets for tests
  - Could not get 2nd and 3rd order modes along hypotenuse with halyard exciters being at the node-line for these modes

Q4M1 exciter at node-line

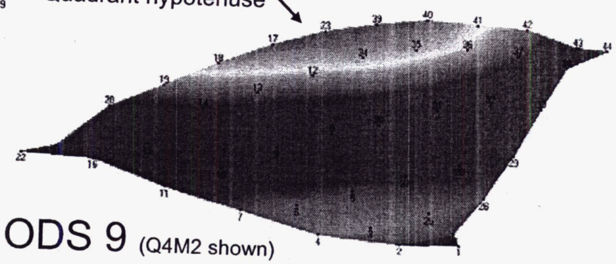


ODS 8 (Q4M2 shown)

2nd bending
Along sail center
Extending from tack-line

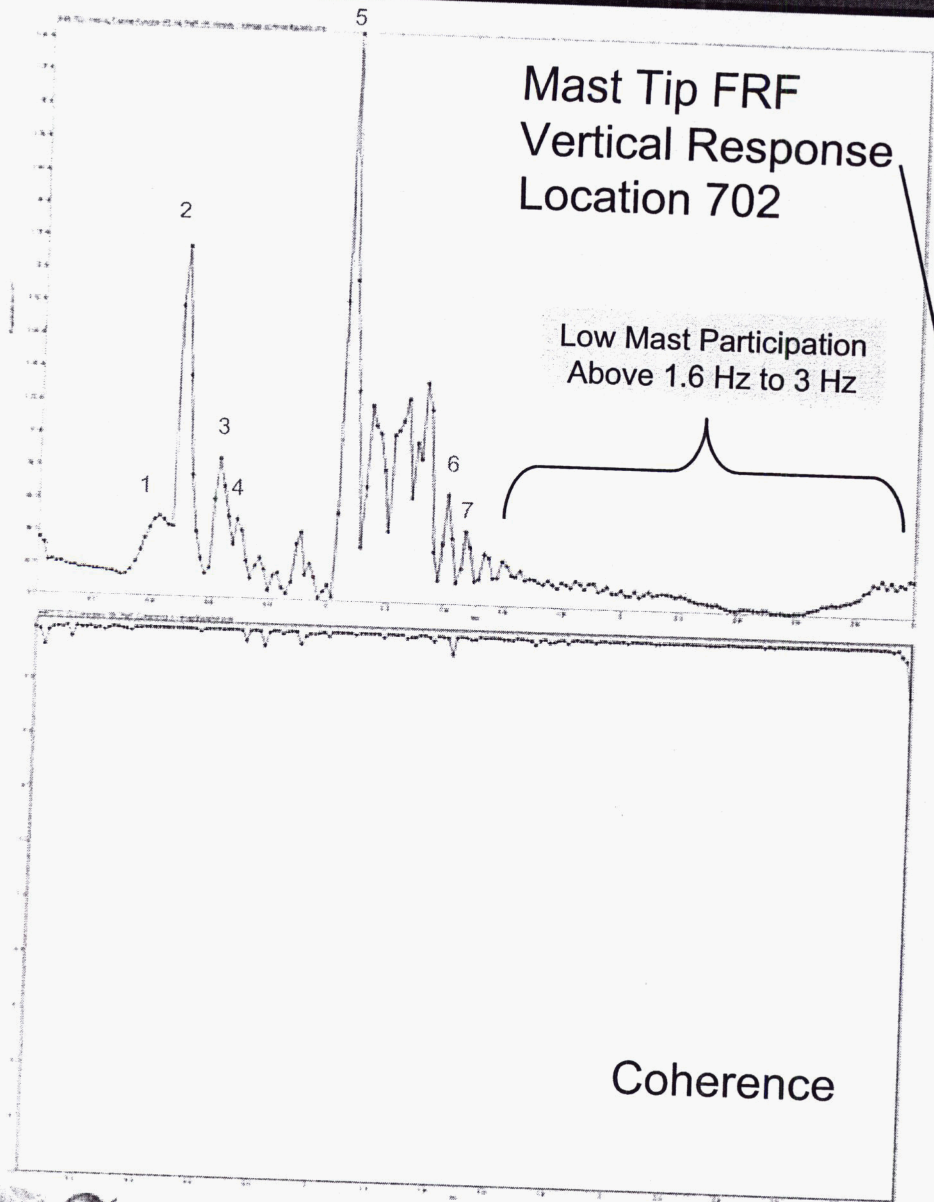
Sail cord 1st bending along quadrant hypotenuse

Quadrant hypotenuse



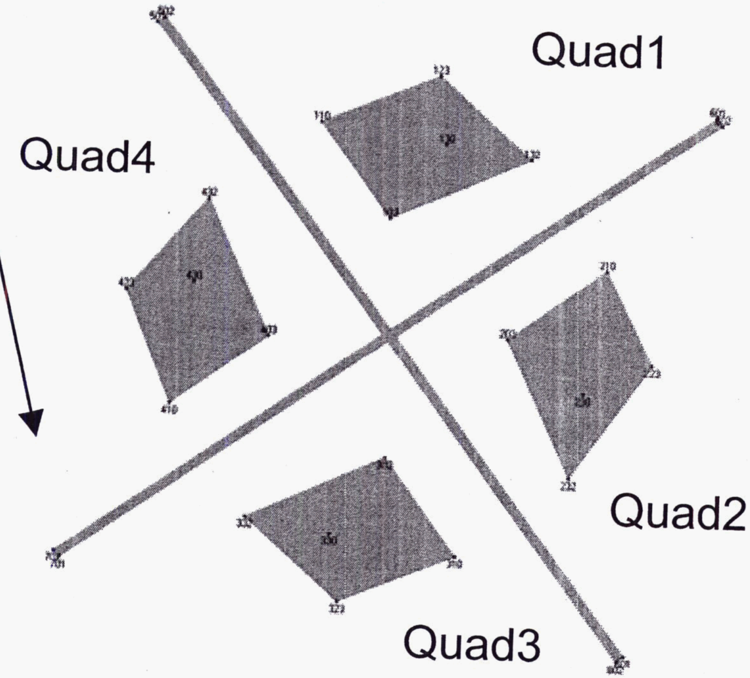
ODS 9 (Q4M2 shown)

20-m Sail Dynamics In-Vacuum – System Test Results (M1 Excitation at each Quad in-phase)

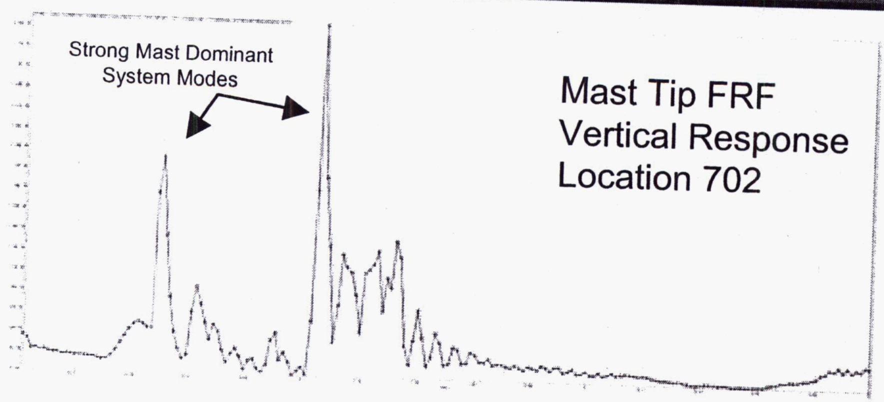


Mast Participation for Dominant Modes

- Mast responds at all 7 modes
- Most significant at 0.5 & 1.06 Hz
  - All mast tips twist in-phase for both modes
- Highly damped response at 0.39 Hz
  - Non-linearity, sliding friction
  - Potential due to negators on halyard and/or mast tip

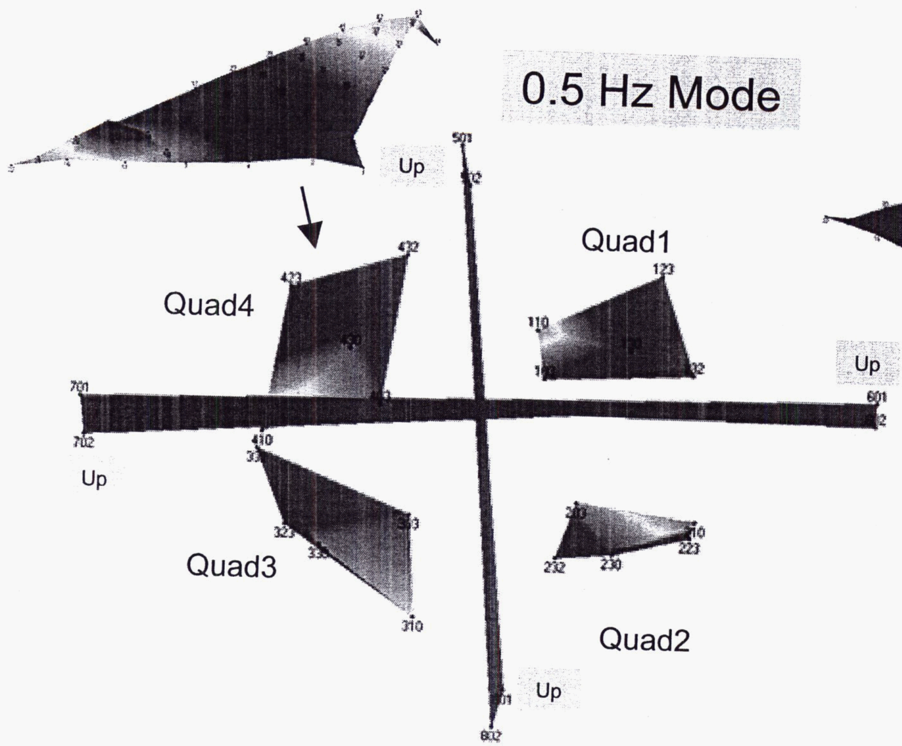


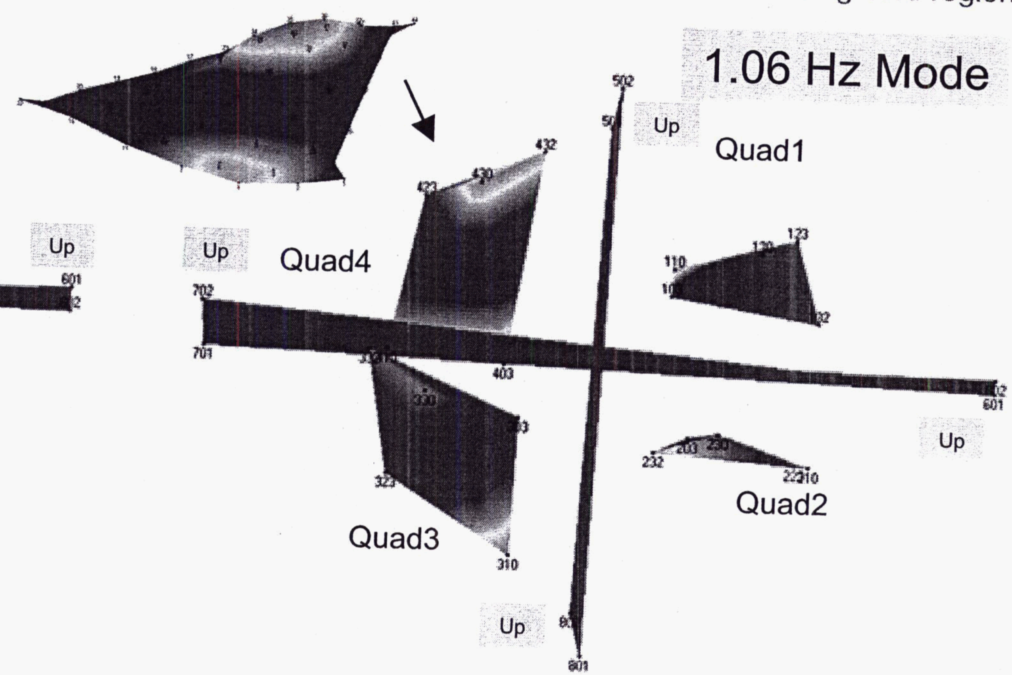
20-m Sail Dynamics In-Vacuum – System Test Results (M1 Excitation at each Quad in-phase)



Strong Mast Dominant System Modes

- Mast Twist with Sail Rocking (0.5 Hz)
  - **1st Fundamental System Mode of Solar Sail**
  - All mast tips twist in-phase
  - All sail quadrants rock in-phase
  - "Pin Wheel Mode"
- Mast Twist with Sail Asymmetric (1.06 hz)
  - All mast tips twist in-phase
  - All sail quadrants bend in-phase
  - Sail bends asymmetrically with LT forward short cord OOP with RT long cord region

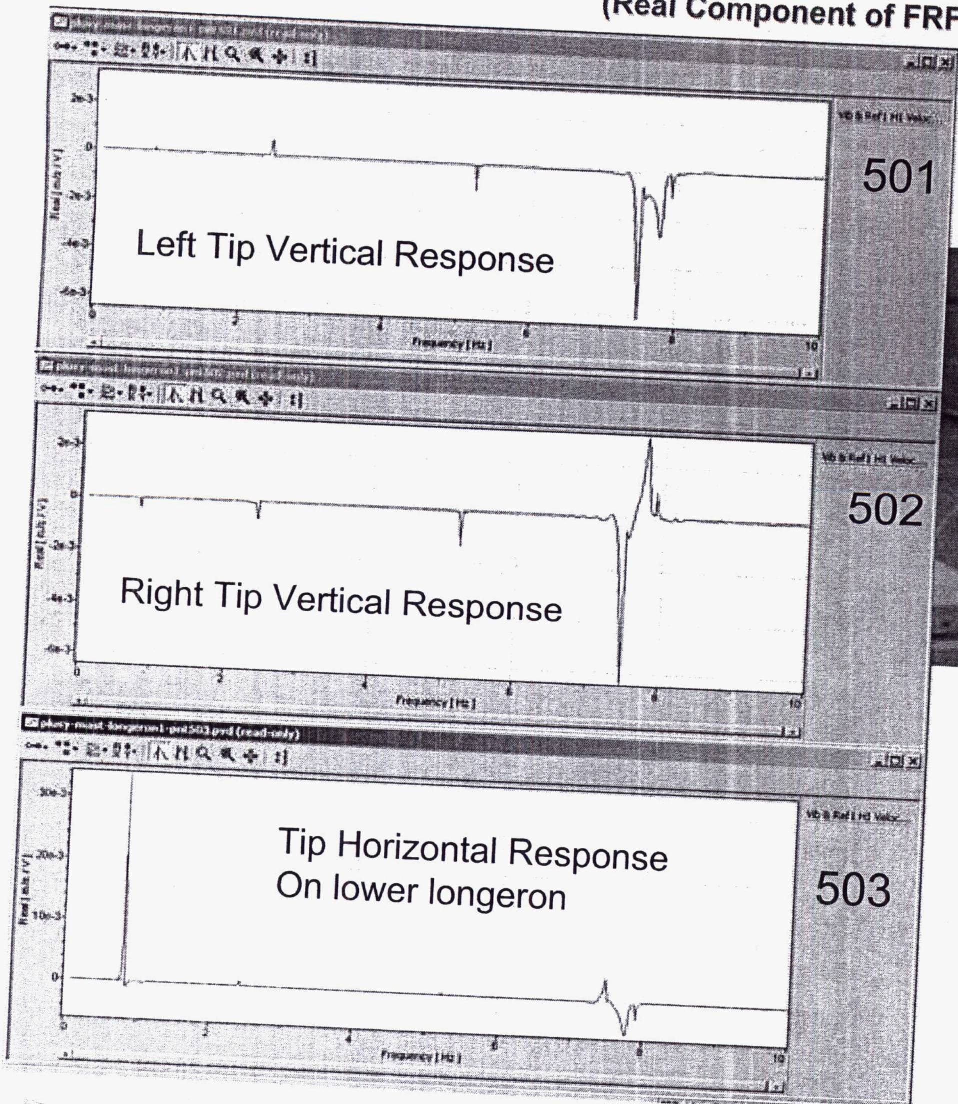




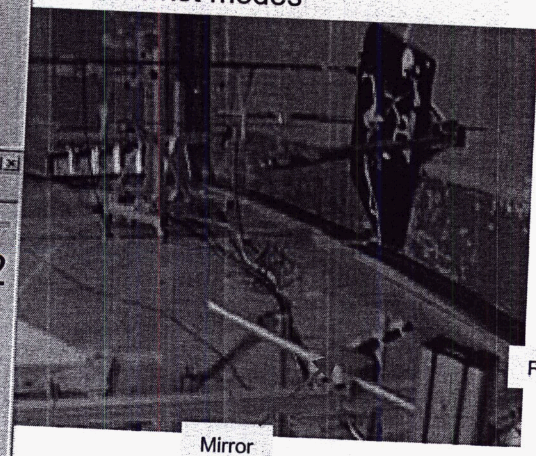
+Y Mast Test in Ambient, with No Sail Attached

2 Vertical Responses (501 & 502), 1 Lateral Response (503)

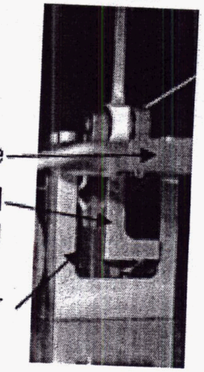
(Real Component of FRF showing Relative Phase)



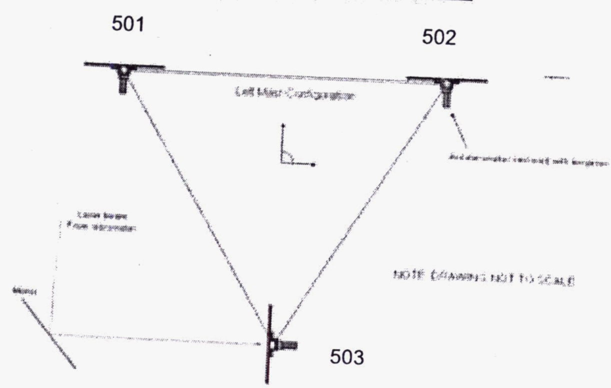
3 Mast Tip Measurements
- resolve mast modes
- vertical modes
- horizontal modes
- twist modes



Excitation Location

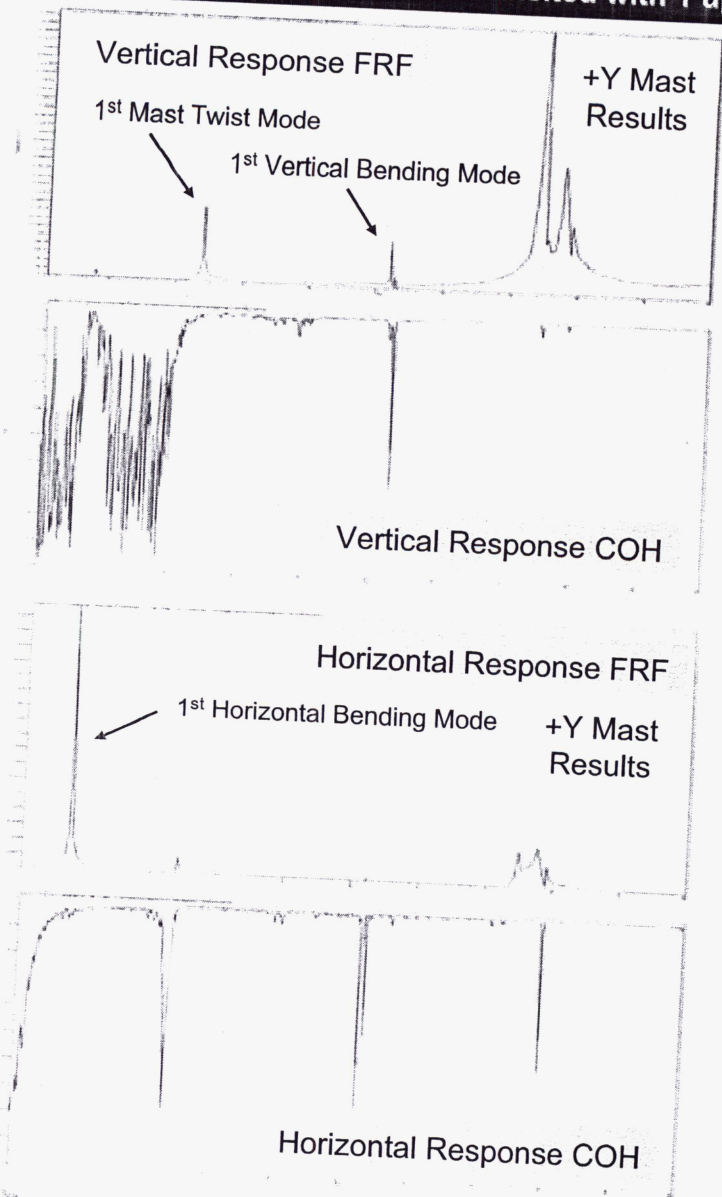


Response Locations



Ambient Mast Tests, with No Sail Attached

(Each Mast Excited with 1 upper longeron PZT Stack at Root to excite bending & torsion)

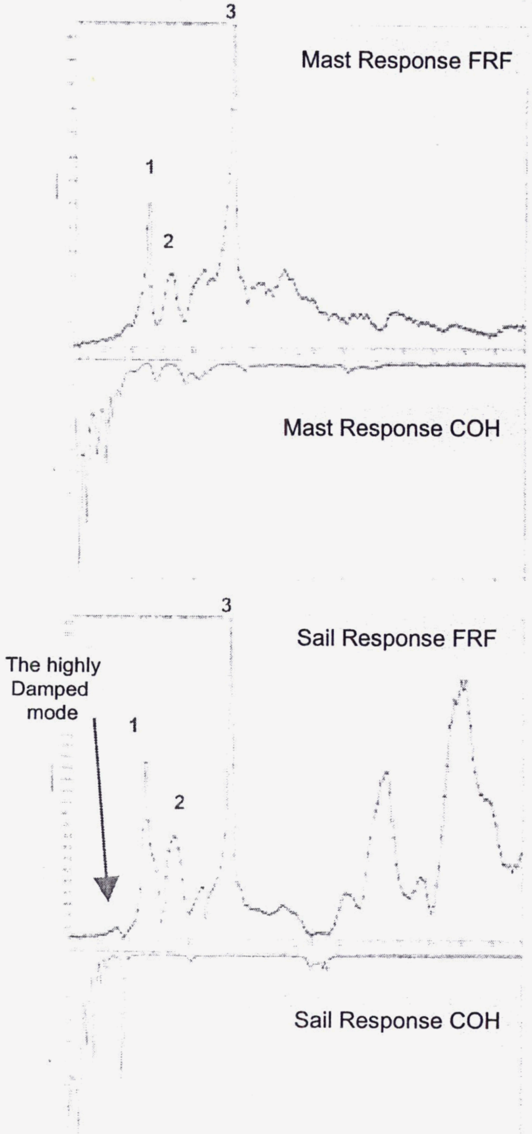


Fundamental Mast Test Modes Identified

- FRF's & Coherences Look EXCELLENT
  - FRF peaks very well defined
  - Excellent Coherence at resonance
- Excellent Consistency
  - All 4 masts show almost identical responses for all fundamental modes
- Piezo Stack Excitation at Mast Root Worked Perfectly
  - Piezo Stack actuators successfully used
  - No shaker test required (saved valuable time)
  - Has traceability to flight testing

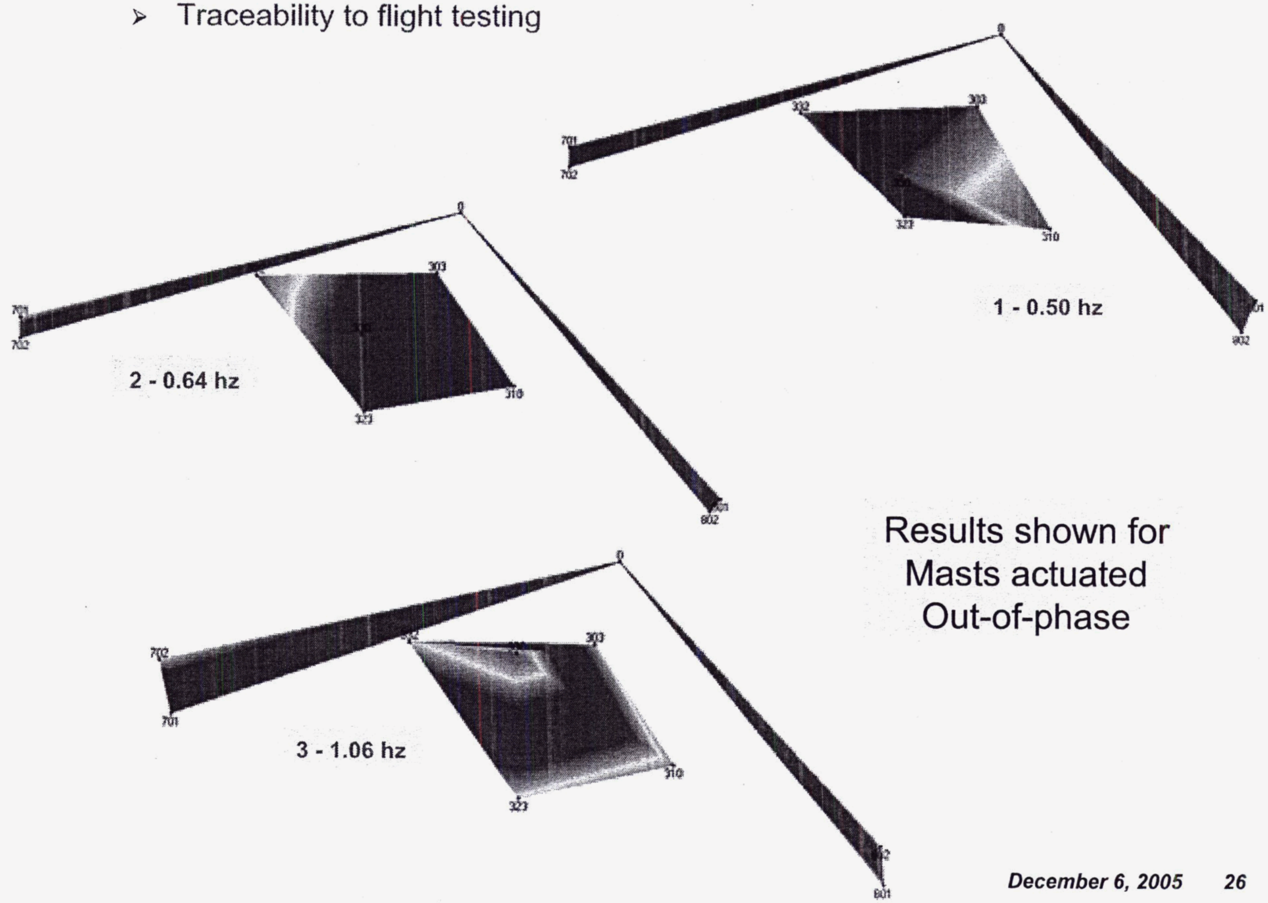
#	Mode Description	Frequency Comparison (Hz)			
		+Y Mast	-Z Mast	-Y Mast	+Z Mast
1	Mast Bending in Horizontal Plane	0.813	0.813	0.797	0.797
2	Mast Twist	2.41	2.39	2.41	2.39
3	Mast Bending in Vertical Plane (-Z Mast)	NA	5.14	NA	NA
4	Mast Bending in Vertical Plane	5.22	5.23	5.27	5.30
5	Mast Bending in Vertical Plane (some twist on –z mast)	7.47	7.50	7.55	7.50
6	Mast 2nd Bending (only mast tips measured)	7.75	7.84	7.75	7.84

20-m Sail Dynamics In-Vacuum – Optional Validation Tests & Special Studies



Sail Excitation Validation Study

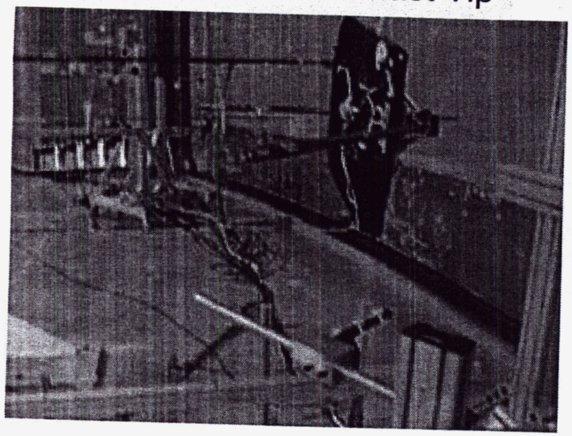
- Piezo stack excitation at mast root
  - **Properly excited fundamental system level "mast dominant" modes**
  - **Identified modes PERFECTLY consistent with BASELINE test results**
  - **Good response on BOTH sail & masts for "mast dominant" modes**
  - Two tests to actuate masts in-phase or out-of-phase with one another
  - Measured Q3 sail and mast tip responses
  - Traceability to flight testing



Results shown for Masts actuated Out-of-phase

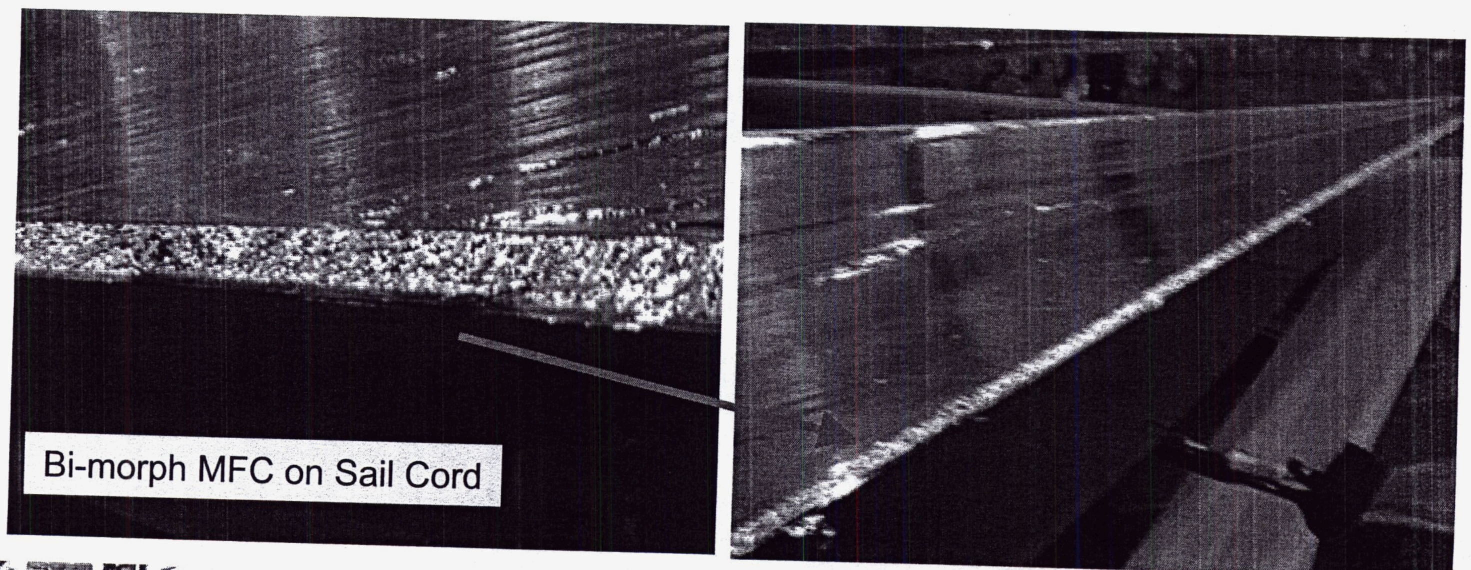
20-m Sail Dynamics In-Vacuum – Optional Validation Tests & Special Studies

Spreader Bar at Mast Tip



Other Validation Tests Completed

- Spreader bar excitation at mast tip
  - ATK demonstrated producing sine sweeps with mast tip spreader bars
  - **Capability for dynamics testing inconclusive**
  - Mast tip counter balance weight severely limits frequency sweep (not flight like)
  - Eccentric mass (counter balance) led to low frequency mast tip swinging motion
- Bi-morph MFC piezo patches on sail cord
  - Bi-morph actuator designed to produce out-of-plane motion for dynamics
  - **6 lbs. cord load on 20-m sail severely restricted actuation performance**
  - **Requires redesigned actuator properly sized for load**
  - 2.5 lbs. cord load on 10-m sail allowed for excellent results
  - Less than 0.5 lbs. load required for on-orbit should allow for good performance
  - Advantage is it can be strategically positioned to identify and control any mode



Bi-morph MFC on Sail Cord

SOLAR SAIL DYNAMICS TEST - Conclusion

EXCELLENT COORDINATION BY TEAM COMPLETED ALL TESTS ON TIME AND SCHEDULE

- Excellent coordination with Plum Brook staff and ATK engineers
- All tests completed as planned on time and schedule
- All test requirements

SAIL SYSTEM DYNAMICS SUCCESSFULLY IDENTIFIED

- Fundamental sail system modes identified
  - Three global "Mast Dominate" system modes (including the 1st system mode "Pin Wheel Mode")
  - Sail Membrane 1st Breathing Mode and numerous higher order "Sail Dominate" modes
  - Nine strong modes identified with high confidence (potentially more after further study)
- Good FRF's and coherences show modes with high confidence
- Excellent repeatability in fundamental modes from test-to-test demonstrated
- Exceeded test requirements by identifying additional higher order modes

MAST DYNAMICS SUCCESSFULLY IDENTIFIED

- Fundamental mast modes identified
  - 1st modes for lateral, longitudinal, and torsional dynamics
- Excellent FRF's and coherences show modes with high confidence
- Exceeded test requirements by identifying additional higher order modes

ALL OPTIONAL VALIDATION TESTS & SPECIAL STUDIES COMPLETED

- Various sail system excitation techniques investigated
  - Piezo stack actuators at mast root
  - Spreader Bar actuation at mast tip
  - MFC patch actuation on sail cord
  - All have traceability to flight testing
- Investigation of air influence on sail dynamics at various pressures
  - Data from Q3 22.5 degree spreader bar sail configuration during chamber repress

Acknowledgements by Gaspar

The following individuals should be acknowledged for their significant contributions to the test effort

- Vaughn Behun (Swales) – Responsible for design & fabrication of all test fixture equipment including the laser pressurized canister & upgrades, SMS mount, vibrometer mount, spring latch for mast tip, etc.
- Troy Mann (Swales) – Collaborates with me for in-vacuum sail testing, post-test quick-look data analysis, and development of DAQ procedures, development of target tracking algorithms for SMS
- Tom Jones, Benny Lunsford, Bill Gould (NASA) – Developed the 5 camera high performance vacuum rated photogrammetry & videogrammetry system, electrical integration of SMS controllers with canister, cabling for camera's & SMS, development of photogrammetry shape test methods
- Wayne Matthews (NASA) & Craig Savencho (Wyle Labs) – Responsible for coordinating and performing a portion of the cabling and electrical development
- Barmac Taleghani (NASA) & Peter Lively (Lockheed) – Pre-test FEM analysis results are used to help identify actuator locations for sail and mast testing
- Guillermo Gonzalez (NASA) – Langley program management for In-Space Propulsion Solar Sail
- Richard Pappa (NASA) – Overall technical POC for Sail work and consultant for dynamic test equipment and utilization issues, development of shape procedures document, independent test data evaluation post-test
- Dave Murphy, Brian Macy & the ATK Test Team (ATK) – Excellent collaboration to successfully complete an aggressive test program with many objectives on time and schedule. Special thanks to the ATK personnel who put in many long days & nights and where instrumental in making the dynamics testing go smoothly while at Plum Brook (i.e. Brian, Ariel, Gab, etc.)
- Jerry Carek, Robin Brown & the SPF Team (GRC Plum Brook) – Excellent hosts for the tests and close coordination with hardware integration issues made for a very successful test program